UNCERTAINTY ANALYSIS OF SHIP POWERING PREDICTION METHODS USING MONTE CARLO SIMULATION

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Uncertainty Analysis of Ship Powering Prediction Methods using Monte Carlo Simulation

By

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Abstract

Model towing tank testing is used to predict the powering required for full-scale vessels. The International Towing Tank Conference of 1978 developed a method that has been in use in its original or modified form in many institutions internationally. Originally the method was solved graphically, utilizing the experience of the analyst, however the use of computers and the automation of the method has impacted the reliability of this approach. Uncertainty analysis has up to this point focused on potential errors in the model data from the tests required to produce the data that is subsequently extrapolated using prediction methods. The overall sensitivity of predicted power from this and other prediction methods to variations in inputs from the model tests and from elements such as the frictional resistance coefficient, form factor or correlation allowance needs to be determined in order to properly interpret the results of an automated analysis. Rather than setting up a series of data reduction equations, a Monte Carlo simulation was used and the entire method was used as the data reduction equation in the uncertainty analysis. The levels of uncertainty in ship powering were obtained for assumed values of uncertainty in the experimental values from tests and for estimated uncertainty in the friction coefficients, wake fraction and wake scaling, thrust deduction fraction, form factor and correlation allowance. Several different extrapolation methods were studied to assess variation in powering prediction methods resulting from variation in input data and from the variation of the details of the extrapolation. These consisted of the ITTC 1978 method, variation that included extrapolation with and without a form factor, different friction lines and correlation allowances, different wake scale and thrust deduction fraction values, and a method that extrapolated from self-propulsion test data only analysed using the same procedure. Uncertainties in the predicted powering results of both methods were compared. Methods of reducing the uncertainty in the predicted power from the ITTC 1978 method were proposed.

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

υ_M	Kinematic viscosity of water for the model test facility, m^2/s
υ_S	Kinematic viscosity of water for the ship, m^2/s
ΔK_Q	Scale effect correction on propeller torque coefficient
ΔK_T	Scale effect correction on propeller thrust coefficient
η_R	Relative rotative efficiency
ρ_M	Water density for the model test facility, kg/m^3
ρ_S	Water density for the ship, kg/m^3
C_A	Incremental resistance coefficient for model-ship correlation
C_{AA}	Air resistance coefficient
C_{F1957}	Skin friction correction coefficient in propulsion test based 1957 method
$C_{FSchlichting}$	Skin friction correction coefficient in propulsion test based Schlichting method
$C_{FGrigson}$	Skin friction correction coefficient in propulsion test based Grigson method
C_{FD}	Skin friction correction coefficient in propulsion test (based on V_M and S_M)
C_{FM}	Frictional resistance coefficient for the model
C_{FM15}	Frictional resistance coefficient for the model at 15°C
C_{FMP}	Frictional resistance coefficient for the model at the propulsion test temperature
C_{FS}	Frictional resistance coefficient for the ship
C_{RM}	Residuary resistance coefficient of model
C_{RS}	Residuary resistance coefficient of ship
C_{TM}	Total resistance coefficient for the model
C_{TM15}	Total resistance coefficient for the model at 15°C
C_{TMP}	Total resistance for the model at the propulsion test temperature
C_{TS}	Total resistance coefficient for the ship
D	Propeller diameter, m

D_{M}	Model propeller diameter, m
D_{S}	Ship propeller diameter, m
F_D	Skin friction correction in self propulsion test, N
Fn	Froude number for the ship and model
g	Gravitational acceleration (9.806 m/s^2)
J_O	Advance coefficient in propeller open water test
J	Advance coefficient for model in propulsion test
k	Form factor
K_{FD}	Skin friction correction coefficient in propulsion test (based on D_M and n_M)
K_{QO}	Propeller torque coefficient in open water test
$K_{QO\mathrm{S}}$	Propeller torque coefficient for full scale propeller
K_{QP}	Propeller torque coefficient in propulsion test
K_{TO}	Propeller thrust coefficient in open water test
$K_{TO\mathrm{S}}$	Propeller thrust coefficient for full scale propeller
K_{TP}	Propeller thrust coefficient in propulsion test
K_{TPod}	Propeller thrust coefficient measured inside pod
K_{TUnit}	Propeller thrust coefficient of pod unit
L_{M}	Model length on waterline, m
L_{S}	Ship length on waterline, m
n_{M}	Model propeller rate of rotation, rps
n_{S}	Ship propeller rate of rotation, rps
N_{S}	Ship propeller rate of rotation, rpm
P_D	Delivered ship power, W
P_E	Effective ship power, W
Q_{S}	Ship propeller torque, Nm
Rn_{M}	Reynolds number for the model
Rn_{S}	Reynolds number for the ship
$R_{T\mathrm{M}}$	Total resistance for the model, N
$R_{T\mathrm{S}}$	Total resistance for the ship, N

S_{M}	Wetted surface area of the model, m^2
S_{S}	Wetted surface area of the ship, m^2
t	Thrust deduction fraction
T_P	Average test temperature for propulsion tests °C
T_R	Average test temperature for resistance tests, °C
T_{S}	Ship propeller thrust, N
V_A	Advance velocity of propeller, m/s
V_{KN}	Ship speed, knots
V_{M}	Model speed, m/s
V_{S}	Ship speed, m/s
w_T	Taylor wake fraction
w_{TS}	Ship Taylor wake fraction

LIST OF APPENDICES

Chapter 1

Introduction

Model towing tank testing has been the primary method of predicting the full-scale power of vessels since the late 1800's (Harvald, 1983). Tow tank testing was first comprised of resistance tests that were used to optimize the shape of the vessel (Manen & Oossanen, 1988) and has progressed to include detailed analysis of the propeller and hull performance that is often paired with numerical work. However, the difficulty in obtaining dynamic similarity between the model and full-scale has yet to be addressed in a way that does not require the use of propulsion factors or correction factors, which are often based on empirical data. For expediency, the term propulsion factor is used here as a general term to describe the scaling and correction factors used in prediction methods. While geometrically similar models of full-scale designs are readily constructed, testing these models in water offers unique challenges. For example, when the powered model is tested in a towing tank the boundary layer of the model is proportionally thicker than the boundary layer of the full-scale ship so a towing force must be applied to overcome the additional resistance.

Model test series have traditionally included three types of tests, which have become standard for predicting full-scale power: resistance tests, propeller open water tests and self-propulsion tests (Manen & Oossanen, 1998). A resistance test measures the drag on the model through the water at a selection of velocities. A propeller open water test measures the thrust and torque of the propeller in uniform or open flow at a selection of advance ratios. A self-propulsion test is closest to modelling the full-scale conditions, a model of the vessel is tested with a model of the propeller and the thrust, torque and shaft speed of the model are measured at a selection of tow forces and propeller loads.

The International Towing Tank Conference "is a voluntary association of worldwide organizations that have responsibility for the prediction of hydrodynamic performance of ships and marine installations based on the results of physical and numerical modeling" (http://ittc.sname.org/). The 15th conference in 1978 proposed a method of powering prediction that incorporated and compromised a uniform solution from many of the methods that were in use in testing facilities around the world at the time. The method was called the ITTC 1978 Performance Prediction Method for Single Screw Ships and since then it has been used in some facilities around the world either in the original or a modified format (many did not include a form factor) however, many facilities did not change their testing approach to make use of the ITTC 1978 method. Although intended for single screw ships, modifications have been made to allow use of the ITTC 1978 method for the prediction of performance from other propulsion configurations such as twin and triple screw ships and ships with pods (NRC-IOT, Atlar *et al.*, 2005). Modifications have been specific to testing facilities and dependent on the experience of the tanks. Such changes have included altering the number and types of tests used to collect data and changing or excluding propulsion factors used to scale the data (Holtrop, 2001, Bose *et al.*, 2005, Table 5.3). The 24^{th} ITTC Powering Prediction Committee reported on current powering prediction methods and when the committee surveyed institutions regarding decisions made in powering prediction procedures (Bose *et al.*, 2005, Table 5.3) the committee found many that use extrapolation methods that incorporate aspects of the ITTC 1978 method but are sufficiently different that they can be considered alternate methods.

Although some of these methods and modifications have been in use for many years the overall stability of these methods is not fully understood. It is not clear how uncertainty in the model test values such as thrust or torque or in the propulsion factors such as wake fraction or form factor, used to account for the flow over the propeller and hull (Manen & Oossanen, 1998), affect the uncertainty in the predicted power. ITTC committees have given guidelines on how to estimate uncertainties from the testing equipment in model tests (ITTC Recommended Procedures, 2002, 2002a, 2002b), which provide the uncertainty in measured values such as thrust and torque. Insel *et al.* (2005) have examined uncertainty in obtaining the form factor. When these parameters are used to extrapolate full-scale powering, the impact of the uncertainties in the prediction of power when propagated through an extrapolation method is of considerable interest to the ship model testing community.

The 24^{th} ITTC Powering Prediction Committee collected a large database of model powering test data with corresponding full-scale powering trials results from a number of testing facilities (Bose *et al.*, 2005). This database is designated the ITTC 2005 Ship Database and was made available to this study. The database was a valuable resource that enabled the author to make an extensive comparative analysis of the uncertainty in predicted power when extrapolating model test data to full-scale.

Each model test data set in the database was collected for vessel powering analysis that used prediction methods requiring three physical tests, resistance, propeller open-water and self-propulsion. All but one set of self-propulsion data were tested using the continental or non-load varying method of model testing (Lindgren *et al.*, 1978). The ITTC 1978 method can be used to predict full-scale power from self-propulsion data that is obtained from either continental or load varying styles of testing, which means that the entire database could be used to examine the ITTC 1978 method. Powering prediction using load varying self-propulsion tests only however, require results from load varying self-propulsion tests so only one data set was available to evaluate that method. The Quasi-Steady method is another model testing method described in Holtrop and Hooijmans (2002) and was developed to reduce testing time. The quasi-steady method assumes that the instantaneous condition of a self-propulsion model test represents the steady condition, the rotative speed of the propeller is gradually varied while the forward speed is kept constant so that the load on the propeller continuously changes during the run; results of tests that use this method were not available in the ITTC 2005 Ship Database and are not readily available so this method was not studied. The ITTC 2005 Ship Database therefore allowed the author to perform an extensive analysis of the traditional ITTC 1978 powering prediction method and its variations and then a detailed comparison of this method with one using data from a load varying self-propulsion test only.

Ship powering prediction methods are used to estimate full-scale operating parameters by propagating the results of model tests through a series of equations based on scaling principles which include propulsion factors and a frictional coefficient used to accommodate for factors that are a challenge to measure, such as ship hull frictional resistance and wind resistance, (Manen and Oossanen, 1988). Traditionally the uncertainties of the full-scale values are estimated from the model test results by using the bias error of the measurement devices and repeated or replicated test runs, and then propagating the errors with the measured values through the equations of the method (ITTC Recommended Procedures, 2002, 2002a, 2002b) using techniques such as those described by Coleman and Steele (1999, pg. 241) and Taylor (1997, pg. 73). This method of determining the uncertainty of the ship parameters allows the analyst to estimate the potential uncertainty based on measurement, but cannot be adequately used to determine the uncertainty of the coefficient of friction and the propulsion factors. Also, this method does not allow the analyst to clearly determine how the powering prediction procedure itself affects the propagation of the uncertainty of the measured value. Does the propagation of measured values through a series of equations increase or decrease the final error of the predicted power? How do the individual tests affect the value of the uncertainty in the final results?

It is possible to follow the error of one measured value, e.g. thrust, through the prediction method and to examine the change in the error with each calculation. This however becomes complex when the uncertainty of more than one value is of interest or when the value of the uncertainty is estimated over a range of numbers rather than one number. Therefore it was proposed that a Monte Carlo simulation be used to examine the effect of the uncertainty of the values measured in model testing, the coefficient of friction and the propulsion factors on the overall stability of extrapolation methods.

In a Monte Carlo Simulation, an input value to a data reduction equation is randomly varied by a predetermined uncertainty and a distribution of the output result is obtained (Coleman & Steele, 1999). In this case the "data reduction equation" is the entire extrapolation method. For all prediction methods studied, the selected values that were examined using the Monte Carlo simulation were varied in a normal distribution in a pre-determined representative range and the effect of this variation was observed by examining the change in predicted full-scale power.

In order to conveniently vary individual values, combinations of values and values with different uncertainty ranges, the Monte Carlo simulation needed to be automated. Programmed versions of both the base ITTC 1978 method and a powering prediction method that uses the results of load varying self-propulsion tests only described here in chapter 2 and designated the E2001 method were available from previous work by Molloy (2001). The programs were modified to allow detailed analysis of components of the method and an automated randomizing feature was added to perform the Monte Carlo Simulations. Details of the program and how the variations were applied are described in Chapter 2.

The ITTC 1978 method in its traditional format was studied first, as described in Chapter 3. The impact of varying the values obtained from the three traditional tests on the predicted power was examined in three stages: the effect of the values varied together, the effect of varying the results of one test and then the effect of varying each of the test results alone. The coefficient of friction and propulsion factors were studied next. The program was run with combinations of the different coefficient of friction and propulsion factors varied together and then varied with the test results added to the combinations.

The E2001 method was studied using Monte Carlo Simulation, as described in Chapter 4, and the same combinations of varied test results, coefficient of friction and propulsions factors as those studied in Chapter 3 were used. The resulting variations in predicted power were compared to those obtained using the ITTC 1978 method.

The original proposal for this project included plans to investigate the development of an extrapolation method for podded propulsors. One of the primary issues to be addressed in predicting power from pod data is the measurement of resistance of the pod itself so a systematic geometric series was designed to determine the effect of geometry on the performance of a pod propeller and to evaluate methods of resistance estimation. Unfortunately due to the lack of available full-scale trials data for ships fitted with podded units, and due to delays in the manufacture of testing equipment it proved impossible to complete this task in the time available. One round of testing of the systematic series was completed and there are preliminary results from the tests of the geometric series and initial evaluations of resistance estimation methods presented as Addendum I.

Using the information gained in Chapters 3 and 4 regarding the range of predicted power expected when there is the uncertainty in model test results and coefficient of friction and propulsion factors, recommendations for improvement in the stability of the ITTC 1978 method are presented in Chapter 5. The overall comparison of the ITTC 1978 and E2001 methods and the relevance of this work to powering prediction are presented in the conclusions in Chapter 6.

Chapter 2

Background

2.1 ITTC 1978 Ship Powering Prediction Method

A committee was formed for the 1978 International Towing Tank conference to develop a ship powering prediction method that could be recommended as a standard for the testing community. The committee used aspects of power extrapolation methods that were in use in major testing facilities at the time and compared the results of different methods with full-scale trials data. The committee then combined a selection of techniques to form the 1978 Powering Prediction method for Single Screw Ships, which at the time was presented as an interim solution (Manen and Oossanen, 1988).

The method used the test results from a scaled geometrically similar model of a full-scale vessel and, using scaling principles as well as empirical formulae to correct for scaling effects due to physical testing limitations, predicted the full-scale operating parameters of the model e.g. power, thrust. In traditional towing tank tests the model values of the

Froude number, $F_n = \frac{V}{\sqrt{gL}}$ and the Reynolds number, $R_n = \frac{VL}{\upsilon}$ cannot be tested simultaneously (Harvald, 1983) and because the Reynolds number is not high enough in model tow tank testing the results cannot simply be multiplied by a scaling factor. This dynamical dissimilarity between the model and full-scale means that techniques must be used to correctly scale the model test results. The ITTC 1978 method recommends a number of factors developed to account for these differences, such as a frictional resistance coefficient, a wake scaling and an air resistance scaling among others (Lindgren *et al.*, 1978). For expediency the term "propulsion factors" is used here as a general term to describe the scaling factors: wake fraction, form factor, correlation allowance and thrust deduction fraction.

The Physical Tests

The ITTC 1978 method is used to extrapolate the results of three physical model tests to full-scale power. The three different tests are a resistance test, a propeller open water test and a self-propulsion test. The resistance test is a bare hull tow test; the drag or resistance of the model vessel, R_{TM}, is measured at a number of different carriage velocities, V_{RM}, without the propeller installed. The resistance is then used to calculate the total resistance coefficient of the model, $C_{TM} = \frac{R_{TM}}{\frac{1}{2}\rho_M V_M^{\ 2} S_M}$ which is extrapolated to ship scale. The total model resistance is broken into two components: frictional and residuary resistance. The frictional resistance is estimated using the ITTC 1957 ship model correlation line, $C_{F1957} = \frac{0.075}{(\log_{10} Rn_M - 2)^2}$. A form factor, k is used to represent the three-dimensional form of the vessel and is estimated from the results of the resistance test using the method proposed by Prohaska (Manen & Oossanen, 1988). The residuary resistance coefficient, $C_{RM} = C_{TM} - (1+k)C_{FM}$, is calculated and is considered to have the same value at model and full-scale $C_{RM} = C_{RS}$ (Lindgren *et al.*, 1978, Harvald, 1983).

The ship scale coefficient of resistance is $C_{TS} = (1+k)C_{FS} + C_{RS} + C_A + C_{AA}$ where C_A and C_{AA} are propulsion factors that account for the differences in model and full-scale hull roughness and air resistance (Harvald, 1983) although in practice the correlation allowance, C_A is a more general correction than just a roughness correction.

The propeller open water test is performed with the model propeller operating in uniform flow without the model hull. The thrust coefficient, $K_{TM} = \frac{T_M}{\rho_M n_M^2 D_M^4}$ and the torque coefficient $K_{QM} = \frac{Q_M}{\rho_M n_M^2 D_M^5}$ are measured at a selection of advance coefficients ($J = \frac{V_M}{n_M D_M}$) (Lindgren *et al.*, 1978, Harvald, 1983).

The self-propulsion test models the ship operating conditions; appendages can be in place and the propeller is operating in the model wake. Due to the difference in the frictional coefficients between the model and full-scale and the allowance at the full-scale for roughness the model is pulled with a force that is equal in magnitude to $F_D = \frac{1}{2}\rho_M V_M^2 S_M[(1+k)(C_{FM} - C_{FS}) - C_A]$. The force allows the model to be towed at the ship self-propulsion point (Manen & Oossanen, 1988). The F_D force is non-dimensionalised using $K_{FD} = \dfrac{F_D}{\rho_M n_M^{\ 2} D_M^{\ 4}}$. In a non-load varied or continental test series the model is pulled at exactly the tow force value calculated for the advance velocity (J) of the test and the thrust and torque coefficients are measured (K_{TM} & K_{QM}) at this point. In a load varied test the model is towed at a number of tow force values and the results of the tow force at the self-propulsion point are interpolated at the intersection of the measured K_{FD} curve and the curve $\dfrac{K_{FD}}{J_P^{\ 2}} = \dfrac{C_{FD} S_S}{2 D_S^{\ 2}}$ (see Figure 2-1), where $C_{FD} = C_{TMP} - C_{TS}$, $C_{TMP} = C_{TM} + (1+k)(C_{FMP} - C_{FM})$, C_{FMP} is the frictional coefficient of the model at the temperature of the self-propulsion test and C_{TM} and C_{FM} are at a standard temperature.

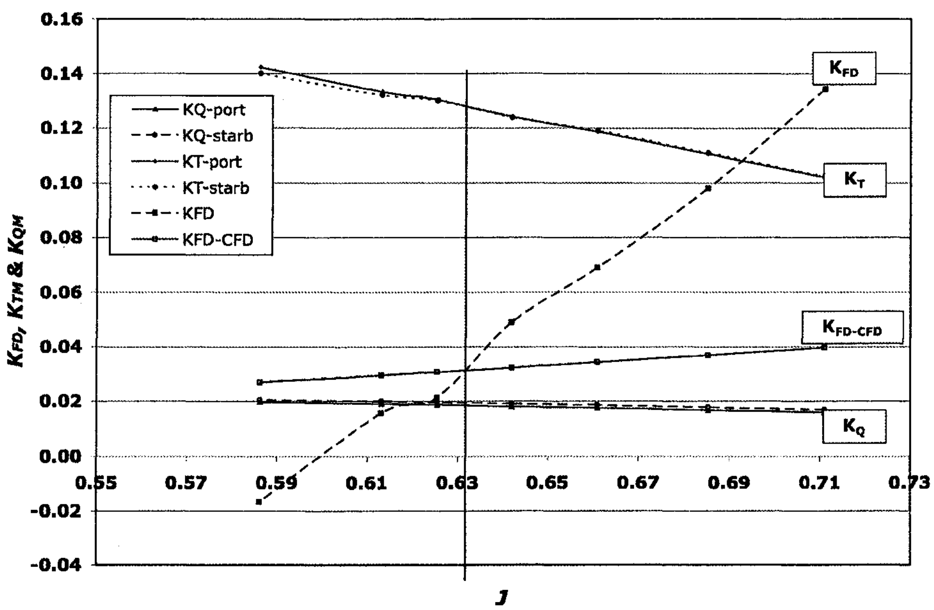

Figure 2-1 Tow force interpolation, example using R-Class data

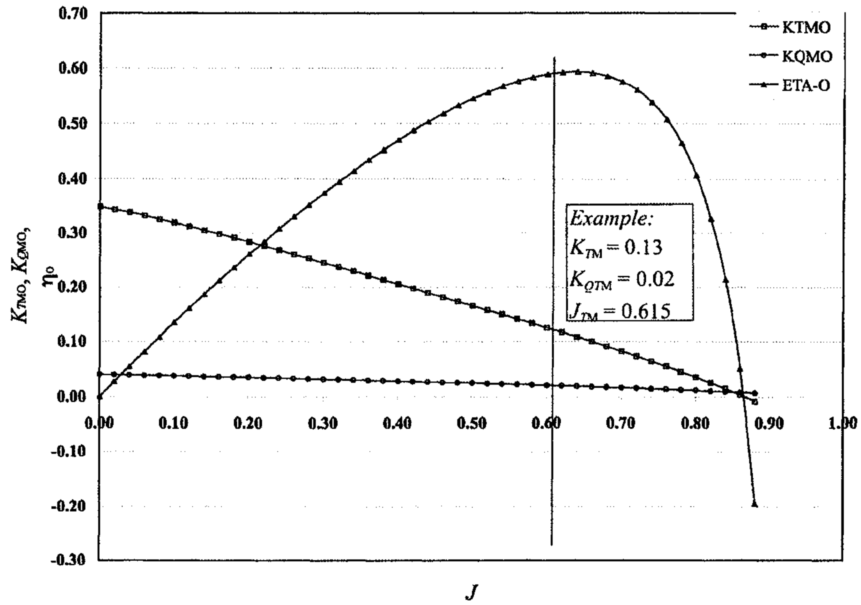

Figure 2-2 Propeller open water test data, R-Class data

Powering Prediction Procedure

The data from all three physical tests are combined in the prediction method. The thrust coefficient, K_{TM} at the self-propulsion point is used to determine the model propeller characteristics K_{QTM} and J_{TM} from the open water data. The thrust coefficient from the self-propulsion test is used as an input to the propeller open water data chart and the corresponding torque coefficient and advance ratio are read. An example is included in Figure 2-2.

The thrust deduction fraction is calculated using data from the resistance and self-propulsion tests, $t = \frac{T + F_D - R_C}{T}$ where R_C is the model resistance corrected to the temperature of the self-propulsion test. The model and ship scale wake fractions,

$w_{TM} = 1 - \frac{J_{TM}}{J}$, where J is the advance coefficient at the self-propulsion point and

$w_{TS} = (t + 0.04) + (w_{TM} - t - 0.04)\frac{C_{VS}}{C_{VM}}$ where $C_{VS} = (1+k)C_{FS} + C_A$ and $C_{VM} = (1+k)C_{FM}$, are the viscous resistance coefficients at ship and model scale (defined by Manen & Oossanen, (1988)), are calculated using data from all three physical tests. The relative rotative efficiency, $\eta_R = \frac{K_{QTM}}{K_{QM}}$ where K_{QM} is the torque coefficient at the self-propulsion point is calculated using the results of the open water and self-propulsion tests (Lindgren *et al.*, 1978, Harvald, 1983).

The open water thrust and torque data (K_T & K_Q) are shifted to represent the full-scale propeller characteristics using designated equations, $K_{TS} = K_{TM} - \Delta K_T$ and $K_{QS} = K_{QM} - \Delta K_Q$ where ΔK_T and ΔK_Q are defined in Manen & Oossanen (1988). This is done because during testing the prevailing flow over the model scale propeller is usually laminar, and the flow over the full-scale propeller is fully turbulent so the difference in the flow is accommodated for using the drag corrections ΔK_T and ΔK_Q (Carlton, 1994).

The wake fraction, thrust deduction fraction and total resistance coefficient of the model are combined with the shifted open water data to determine the ship propeller operating point, interpolated as the full-scale advance coefficient, J_{TS}, and the torque coefficient, K_{QTS} from the intersection of the K_{TS} curve from the open water data and $\frac{K_{TS}}{J^2} = \frac{S_S C_{TS}}{2D_S^2(1-t)(1-w_{TS})^2}$ (Manen & Oossanen, 1988), Figure 2-3. In turn, the full-scale operating parameters are calculated: the shaft speed, $n_S = \frac{(1-w_{TS})V_S}{J_{TS}D}$, the thrust of the propeller, $T_S = \frac{K_T}{J^2} J_{TS}{}^2 \rho D^4 n_S{}^2$, the torque of the propeller, $Q_S = \frac{K_{QTS}}{\eta_R} \rho D^5 n_S{}^2$ and the delivered power, $P_{DS} = 2\pi\rho D^5 n_S{}^3 \frac{K_{QTS}}{\eta_R}$.

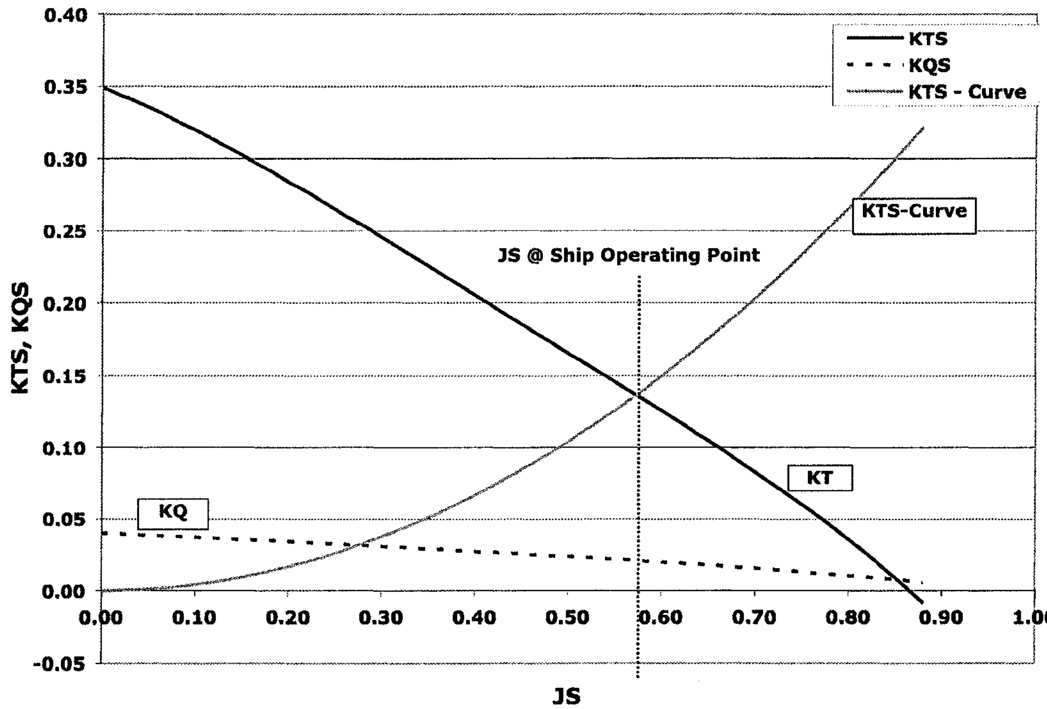

Figure 2-3 Ship propeller operating point example

2.2 E2001 Ship Powering Prediction Method

For brevity the name E2001 is designated to describe a method of ship powering prediction method that uses the results from a self-propulsion test alone. This method was proposed for consideration by the author in early publications including Molloy (2001) and Molloy and Bose (2001). The self-propulsion test is run as a load varying test and the load is varied through a large range of propeller advance coefficients, J values, which includes values that force the propeller thrust negative (values of J greater that the propeller design advance ratio). The purpose of this is to allow propeller thrust and towing force results to be plotted. Normally this plot is found to be linear (Figure 2-4 Molloy, 2001). The line can be described by $F_D = T_M(t-1) + F_{D@T=0}$ where t is the thrust deduction fraction (Iannone, 1997, Molloy, 2001).

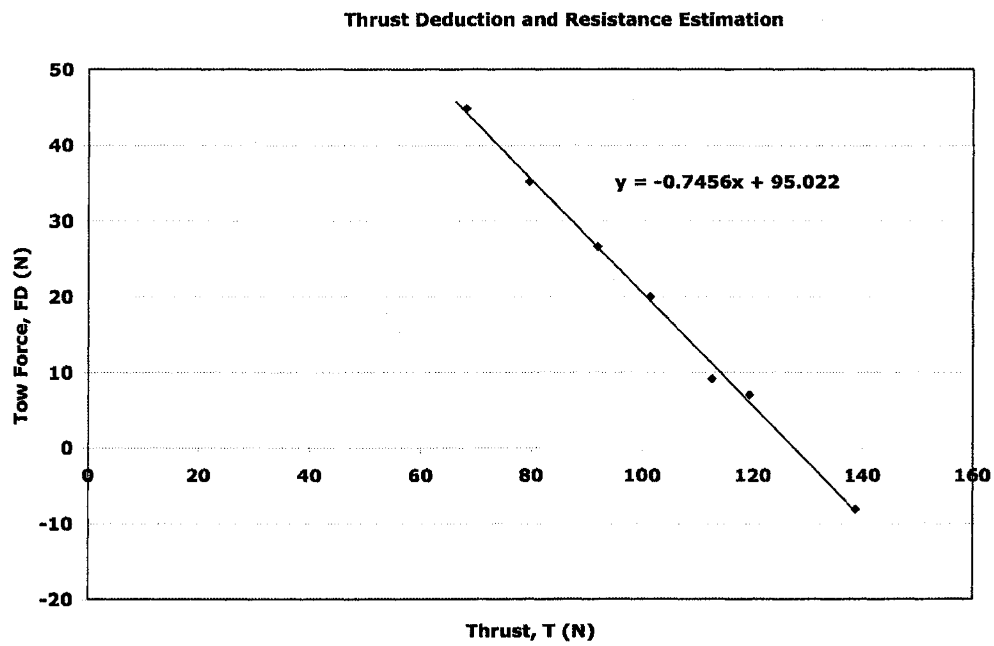

Figure 2-4 Resistance and Thrust Deduction Fraction Estimation

A resistance test is not performed and the resistance of the model can be represented by the towing force at zero thrust, $F_{D@T=0}$ for the ship speed being studied. If the relationship between the propeller thrust and tow force is not linear then a resistance test or alternative method of estimating the resistance could be used although the estimated resistance is not required to extrapolate using this method.

Using the tow force value at zero thrust, $F_{D@T=0}$, the tow force value that allows the model to be pulled at the self-propulsion point of the ship, $F_D = \frac{1}{2}\rho_M V_M{}^2 S_M\left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$ and the thrust deduction fraction, the full-scale thrust can be calculated from:

$$
\begin{aligned}
T_S &= T_M \lambda^3 \frac{\rho_S}{\rho_M} \\
&= \left\{T + \frac{F_D - F}{t-1}\right\}\lambda^3 \frac{\rho_S}{\rho_M} \\
&= \left(\frac{F_D - F_{T=0}}{t-1}\right)\lambda^3 \frac{\rho_S}{\rho_M}
\end{aligned}
$$

where λ is the scale factor, ρ is the density and T and F are any coordinates on the line (Figure 2-4, Iannone, 1997, Molloy, 2001, Holtrop, 2001).

The next step is to determine the ship propeller operating point. The operating point is interpolated from the intersection of the full-scale thrust and torque coefficients. The thrust and torque coefficients are expressed as polynomials (Figure 2-5), determined from the model data using a least squares method, in order to straightforwardly apply the wake scaling directly to the propeller advance coefficient $K_{TS} = a_1\left(w_{scale}J\right)^2 + b_1\left(w_{scale}J\right) + c_1 - \Delta K_T$ and $K_{QS} = a_1\left(w_{scale}J\right)^2 + b_1\left(w_{scale}J\right) + c_1 - \Delta K_Q$, (where ΔK_T and ΔK_Q are described in Manen & Oossanen (1988) and Harvald (1983)).

The interpolation equation $K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S{}^2 V_S^2}$ (Holtrop 2001) intersects with the ship thrust coefficient, K_{TS} and this intersection is the ship propeller operating point, Figure 2-5 (Molloy 2001).

Once the full-scale thrust and the ship propeller operating point are determined they can then be used to calculate the remaining full-scale operating parameters: the shaft speed, $n_S = \sqrt{\left[\frac{T_S}{K_{TS} D_S^4 \rho_S}\right]}$, the ship scale torque, $Q_S = \rho_S n_S^2 D_S^5 K_{QS}$, the delivered power, $P_{DS} = 2\pi\rho_S n_S^3 D_S^5 2K_{QS}$.

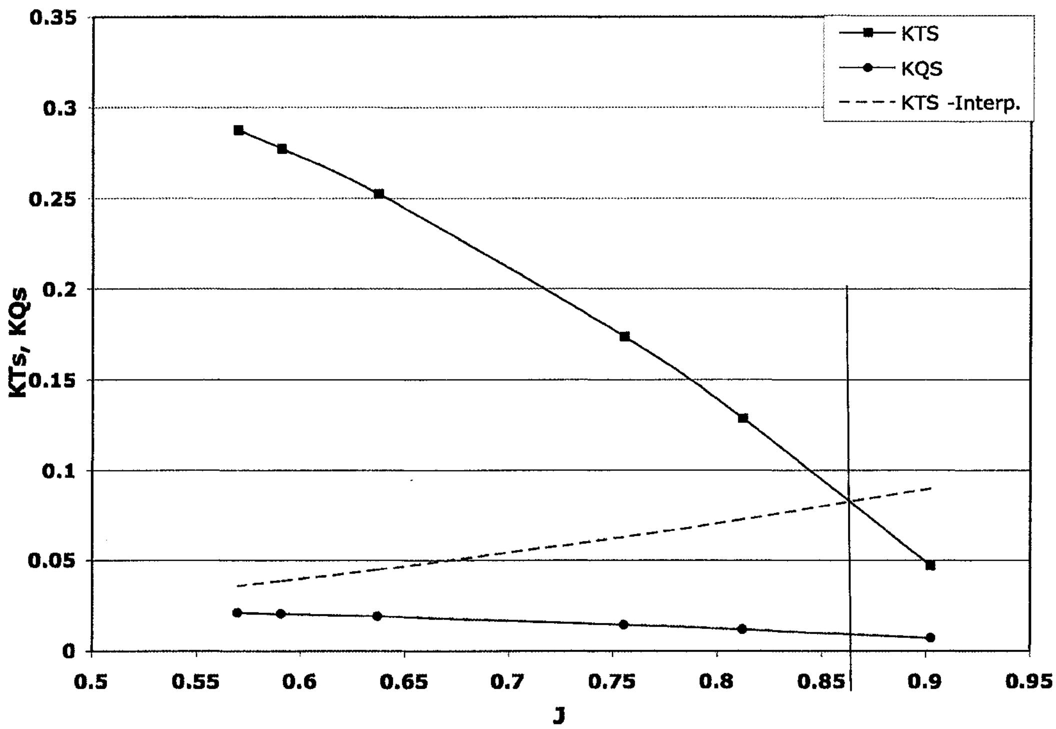

Figure 2-5 Ship Propeller Operating Point determination

The following are incorporated in the E2001 method in the extrapolation of power:

- frictional resistance coefficient, C_F
- form factor, k
- correlation allowance, C_A
- thrust deduction fraction, t

The frictional resistance coefficient can be one of a number of coefficients available, for example the C_{F1957} (Manen & Oossanen, 1988), the C_F proposed by Grigson (2000) or the C_F proposed by Schlicting (1987). The friction lines proposed by Grigson and Schlicting are turbulent friction lines and may more accurately represent the frictional resistance of the vessel than the ITTC 1957 ship model correlation line. The frictional resistance coefficient is used in the determination of the self-propulsion point towing force, $F_D = \frac{1}{2}\rho_M V_M{}^2 S_M\left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$ in the E2001 method and it is not used to calculate or estimate any other values.

The form factor, k, is estimated using a method outlined by Holtrop (2001) that can be used without resistance data and instead use data from the lower Froude number self-propulsion tests. At low Froude numbers, when wave-making is very small, the resistance ($R_M = F_{T=0}$) is approximately equal to the frictional resistance (R_F) times one plus the form factor $(1+k)$ [Holtrop, 2001].

$$R_M = F - T\Big/\left(\partial T/\partial F\right) = F + T(1-t)$$

$$R_M \approx R_F(1+k) \qquad Fn \to 0$$

$$(1+k) \approx \lim_{Fn \to 0}\left[\frac{R_M}{R_F}\right]$$

In the E2001 method the form factor is also used in calculating the self-propulsion point tow force and is not used to calculate or estimate any other values. The self-propulsion point tow force is used to calculate the full-scale thrust, $T_S = \left\{\frac{F_{T=0} - F_D}{1-t}\right\}\lambda^3 \frac{\rho_S}{\rho_M}$.

In lieu of a wake fraction, a wake scale effect, $w_{scale} = \frac{\left(V_A/V \right)_S}{\left(V_A/V \right)_M}$ (Holtrop, 2001), is applied to the thrust and torque coefficients, $K_{TS} = a_1 \left(w_{scale} J \right)^2 + b_1 \left(w_{scale} J \right) + c_1 - \Delta K_T$ and $K_{QS} = a_2 \left(w_{scale} J \right)^2 + b_2 \left(w_{scale} J \right) + c_2 - \Delta K_Q$, to correct the comparatively higher thrust loading at model scale. The value used for the wake scale effect can be determined from a database of correlated model and ship trial data or from a semi-empirical formula such as that presented by Holtrop and Mennen (1982). The reliability of the wake scaling is dependent on the size and diversity of available data. The E2001 method has been shown to predict power that is close in value to that predicted using the ITTC 1978 method and to the corresponding full-scale trials data (Molloy, 2001).

2.3 Database of Ships

The ITTC 2005 powering prediction committee collected a database of ship model tests with corresponding sea trials and it is designated here as "the ITTC 2005 ship database" (Bose *et al.*, 2005). The database contained test data for 48 different ship forms, primarily containerships and ferries with lengths from 40m to 300m (Bose *et al.*, 2005, Figures 6.1 and 6.2).

For this study 21 ships from the database were used and are described in Table 2-1. These 21 sets of data were chosen to represent a large variety of vessel types. The vessel ship operating speed from each model was chosen for the analysis. In the first section of the analysis of the ITTC 1978 powering prediction method all 21 ships are compared.

Table 2-1 Descriptions of ships used in study

Chart Legend	Ship Type	# of Props	Ship Speed m/s
Ship #1	Chemical Carrier	1	7.36
Ship #2	Chemical Carrier	2	7.36
Ship #3	Chemical Carrier	1	7.36
Ship #4	Passenger	2	13.37
Ship #5	RoRo Ferry	2	12.34
Ship #6	Ferry	2	11.83
Ship #7	Passenger Cruise Liner	2	10.28
Ship #8	Ferry	1	5.66
Ship #9	Car Passenger Ferry	2	13.37
Ship #10	Passenger	2	9.77
Ship #11	Cruise Liner	2	11.06
Ship #12	Passenger	2	11.32
Ship #13	Passenger	2	11.06
Ship #14	Passenger	2	8.49
Ship #15	Cruise Vessel	2	10.8
Ship #16	Passenger Cruise Liner	2	12.35
Ship #17	Container Ship	1	8.22
Ship #18	Container Ship	1	8.22
Ship #19	Tanker	1	8.74
Ship #20	Tanker	1	8.48
Ship #21	R-Class Icebreaker	2	8.75

A subset of ships is shaded in Table 2-1: Ships 1, 9, 12, 16, 17 and 21. These ships were used for further detailed study of the extrapolation method; they were chosen to represent a range of vessel types. Ship #21 is the only data set in the database that included load-varied self-propulsion tests and is the only set that could be used to analyse the E2001 method.

2.4 Program

A program written by Molloy (2001) was used to extrapolate ship power from model test data using the ITTC 1978 method. It was designed to take 3 input files that correspond to the three tests that are required in the traditional ITTC 1978 method. The E2001 method could be used simultaneously in the program to predict delivered power if the input data included a load-varied self-propulsion test.

The programmed methods of calculating the ITTC 1978 method and the E2001 method were validated using a line-by-line method. Each line of calculation in the program was output to a file and then each value of each programmed method was compared to each value calculated when the method was solved using a spreadsheet. The spreadsheet used to calculate results using the ITTC 1978 method was validated by the candidate and then sent for an external evaluation by David Cumming of the National Research Council Institute for Ocean Technology in St. John's, NL. Dr. Neil Bose also assisted the candidate in repeat validations of both the spreadsheets and programs. Finally, the results of both the spreadsheets and programs were compared to a number of the data sets in the ITTC 2005 Ship Database (Bose *et al.*, 2005) that included intermediate values in the data file. The author is confident the programmed methods produce valid results.

The first input file contained the results of the resistance test: velocity (m/s) and resistance (N), a copy of the resistance file for ship #16 is found in Appendix A.1. The data in this file were then converted into an equation using a 2^{nd} order regression equation. Higher order equations were investigated by running the program with variation in all measured input values and with first 2^{nd}, then 3^{rd} and then 4^{th} degree polynomial regression equations for the resistance data. The change in standard deviation of the predicted power was very small and the overall impact on the final result was small, (see Figure 2-6), so a 2nd order polynomial was used for the resistance data regression for all data sets. The skew to the right in the curve is explained in section 3.2.3.

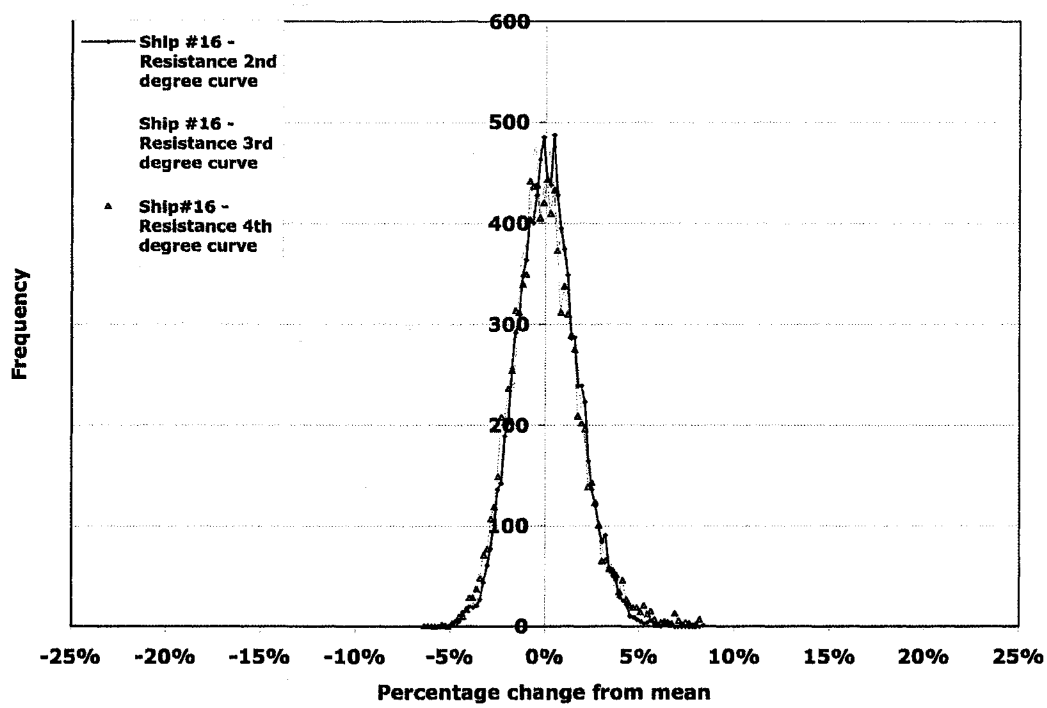

Figure 2-6 Change in predicted power with variation in all measured inputs and including change in degree of regression curve used to represent resistance

The second file contained the results of the open water test, a copy of this file for ship #16 is found in Appendix A.2. The test results were entered into the program in the form $J = \frac{V_A}{nD}$, $K_T = \frac{T}{\rho n^2 D^4}$, $K_Q = \frac{Q}{\rho n^2 D^5}$ (Manen & Oossanen, 1988). K_T and K_Q were converted to a 2nd order equation through regression (Holtrop, 2001).

The third file, two copies of which are found in Appendices A.3 & A.4, contained all the model particulars, the test temperatures and viscosities and the results of the self-propulsion test. The form factor, correlation allowance (Manen & Oossanen, 1988) and wake scaling (used in the E2001 method, Holtrop, 2001) were input directly to the program in the third file and for the purposes of this analysis were not automatically calculated.

A sample of the terms used in the input file is included in Table 2-2. The input file was written in XML® and the program was written in Java®.

Table 2-2 Sample of terms used in input file

Description	[illegible]
Viscosity	**<VISSPS>**1.65988E-6</VISSPS>
Scale	**<SC>**25.21</SC>
Length of model	**<LM>**6.843</LM>
Breadth of model	**<BRDT>**0.952</BRDT>
Draught of model	**<DRGT>**0.248</DRGT>
Self-propulsion test velocity	**<VELOCITY>**2.6637157894977</VELOCITY>
Shaft speed	**<REVOLUTIONS>**13.14</REVOLUTIONS>
Total thrust	**<TOTAL_THRUST>**85.5432</TOTAL_THRUST>
Standard deviation for velocity	**<COLUMN NAME="VELOCITY" DELTA=**".02663"/>
Standard deviation for shaft speed	**<COLUMN NAME="REVOLUTIONS" DELTA=**".1314"/>
Standard deviation for total thrust	**<COLUMN NAME="TOTAL_THRUST" DELTA=**"0.855432"/>
Standard deviation for correlation allowance	**<CONSTANT NAME="CA" DELTA=**"0.0002"/>
Number of iterations & file name	**<RANDOMIZATION ITERATIONS=**"10000" FILENAME_MOD="all">
Parameters to be varied: total thrust & velocity	**<COLUMN NAME=**"TOTAL_THRUST"/> **<COLUMN NAME=**"VELOCITY"/>

This file also contained the value of the standard deviations of each parameter (referred to as 'Delta' in the program), the propulsion factors that were varied, and instructions to the program on which value(s) should be varied for each run of the program.

The program read in the regression curves and the third input file and determined the resistance at the velocity of the self-propulsion test. Examples of values calculated within the program are given in Table 2-3.

Table 2-3 Examples of values calculated in program

Constant	Definition
Fn	Froude number of test
R_N	Reynolds number of test
C_{F1957}	Coefficient of Friction calculated using the 1957 equation
C_{TM}	Total resistance coefficient of the model

If the self-propulsion data were load-varied, the self-propulsion point was interpolated using the tow force coefficient, K_{FD} (as discussed above, Manen & Oossanen, 1988) and the thrust identity was then used to determine the J and K_Q values from the open water regression curves (Harvald, 1983). If the data was non-load varying, J and K_Q were determined from the self-propulsion values in the input file.

2.4.1 Variation using Monte Carlo Simulation

Randomisation was achieved using the Monte Carlo method of simulation. In a Monte Carlo Simulation, an input value to a data reduction equation is randomly varied by a predetermined uncertainty and a distribution of the output result is obtained (Coleman & Steele, 1999). In this case the "data reduction equation" was the entire extrapolation method. The original value was input to the program, assigned a standard deviation and distributed normally. Each output value was presented as a mean value with a standard deviation in a normal distribution. The method of randomisation was validated by taking a selection of the values that were randomised using the program and then comparing each calculated output result with the output results of similarly varied values calculated using a spreadsheet. The input values to each method were varied 5-10 times using a spreadsheet and the values were randomly chosen within the assigned standard deviation. The results of calculations made when the input values were varied with a spreadsheet compared well with those results calculated using input values varied within the program. The randomiser in the program first randomly varied the resistance test results in a normal distribution with a standard deviation of 1% of each measured value. The resistance test results were presented as a set of runs with a velocity and a resistance for each run.

Table 2-4 Example of Randomised Resistance Test Values

Original Values		Randomised Values, Iteration #1	
V_M m/s	R_M @ 15C N	$V_{M\text{-}Random1}$ m/s	$R_{M\text{-}Random1}$ N
0.577	4.92	0.586	4.77
0.692	7.09	0.689	7.31
0.807	9.58	0.819	9.20
0.922	12.32	0.895	13.17
1.038	15.39	0.989	15.61
1.153	19.04	1.193	19.18
1.268	23.52	1.254	24.85
1.384	28.78	1.394	29.09
1.499	34.51	1.486	36.47
1.614	40.38	1.581	40.15
1.730	49.88	1.719	49.95
1.845	70.07	1.841	71.91
1.960	98.88	1.983	98.83

A regression equation was calculated to represent the data in the file and was then input to the program. If the analysis required the velocity and resistance to be randomised then all the measured values in the file were randomised (see Table 2-4). This process was repeated the number of times that was specified in the program (in this case 10,000) and once each value in the file was randomised, a new regression equation was calculated using the new data set and that equation was input into the extrapolation program.

The same process was followed to randomise the open water data. Again, the data was presented as a file of test results from a large number of test runs. The data points in the file that contained the open water data were represented by a regression equation and input in this manner to the program. Once the data in the file were randomised a new regression equation was calculated and this equation was input to the program. This process was repeated the required number of times.

Table 2-5 Example of Randomised Self-Propulsion Test Values

Parameter	Original Value	Standard Error	Randomised Value
Velocity (m/s)	1.957	0.020	1.935
Revolutions (rps)	15.900	0.159	15.612
Tow Force (N)	-8.100	0.448	-8.432
Torque Port (Nm)	2.040	0.020	2.041
Torque Stbd (Nm)	2.120	0.021	2.132
Thrust Port (N)	69.900	0.694	68.843
Thrust Stbd (N)	68.800	0.694	68.244

The self-propulsion data were varied directly; there was only one value that represented the self-propulsion point velocity, one value of the self propulsion point thrust, one torque value, one shaft speed and one tow force value, so each term in the file that was required to be randomised was varied and then input to the program, Table 2-5 shows the randomised values of one data set. This was repeated the required number of times (10,000).

Variation of the other propulsion factors occurred in 2 ways. Propulsion factors were input to the program if they were not calculated using equations within the method. Factors such as the correlation allowance, which could be location specific, were randomised before they were input to the program, as were the resistance, open water and self-propulsion data.

If the factor was calculated using equations within the program (e.g. frictional resistance coefficient) and the analysis required the value to be studied alone, then a direct variation was made within the program. The variation was added to the calculated value, the variation had an initial value of zero and a standard deviation was applied that was an estimated representative (pre-determined) amount for the value being varied. Example: $C_{F1957} = \frac{0.075}{(\log_{10} Rn_M - 2)^2} + Variation$, where *Variation is* ± random value with pre-assigned standard deviation.

The standard deviations of these factors were chosen based on technical judgment and were not always 1% of the maximum value. For example, the model frictional resistance coefficient standard deviation was the difference between C_{F1957} and $C_{F\mathrm{Grigson}}$ at model scale, this is explained in detail in Chapter 3.

Chapter 3

Variation in ITTC 1978 Powering Prediction Method

The ITTC 1978 powering prediction method is an extrapolation method proposed by the 15th International Towing Tank Conference in 1978 that incorporated many of the powering scaling tools that were in use at facilities around the world at the time (Lindgren *et al.*, 1978). The method is described in its entirety in the committee report from 1978 and in Principles of Naval Architecture II (Manen & Oossanen, 1988) and briefly in Chapter 2. The committee examined various ways of extrapolating model test data and proposed a method for single screw ships that addressed among other issues the friction on the vessel hull, the wake of the vessel and the air resistance. The ITTC 1978 method or aspects of the method have been in regular use at facilities around the world since then and it is used beyond the extrapolation of single screw model test data. The method has also been used to extrapolate model test data for twin, triple and quadruple-screw ships, and ships fitted with podded propulsors among others. Incorporated within the traditional 1978 method are a number of propulsion factors and a frictional resistance coefficient, C_F, used to account for the difficulty in obtaining dynamical similarity between model and full-scale vessels (Harvald, 1983). Propulsion factors include:

- a form factor, k
- a thrust deduction fraction, t
- a wake fraction, w
- a correlation allowance, C_A
- a relative rotative efficiency, η_R

The frictional resistance coefficient is used to approximate the frictional resistance of the model and then scale it to ship values using either a model-ship correlation line such as the ITTC 1957 correlation line (Manen & Oossanen, 1988), or a turbulent flat plate friction line such as that proposed by Schlichting (1987) or Grigson (1999) or the American Towing Tank Conference, ATTC, (Schoenherr) friction line (Manen & Oossanen, 1988). The ITTC 1957 correlation line and the friction lines are based on flat plate friction over a range of Reynolds Numbers and not on ship model friction so a form factor, k, is often applied to the frictional resistance coefficient to account for the three dimensional shape of the vessel, the value of k is assumed to be the same at model and full scale.

The thrust deduction fraction, t, is the fraction of the total thrust that is used to represent the loss of thrust caused by the low pressure region as the flow speeds up on entry to the propeller. This value is assumed to be the same at model and full-scale (Harvald, 1983). The wake fraction is the difference integrated over the disk of the propeller between the velocity of the ship and the inflow velocity to the propeller. During model tests, the model-scale vessel has a boundary layer with a scaled thickness greater than the equivalent full-scale ship so the wake needs to be scaled (Carlton, 1994). In the ITTC 1978 method the full-scale wake, $w_{TS} = (t + 0.04) + (w_{TM} - t - 0.04)\frac{C_{VS}}{C_{VM}}$ is determined using the model wake, $w_{TM} = 1 - \frac{J_{TM}}{J}$, thrust deduction fraction, $t = \frac{T + F_D - R_C}{T}$, the frictional resistance coefficient ($C_{VS} = (1+k)C_{FS} + C_A$ and $C_{VM} = (1+k)C_{FM}$) and for single screw ships an added factor (0.04) to account for the effect of the rudder, if the ship is twin screw or greater this factor is deleted (Manen & Oossanen, 1988). If the wake of the ship is found to be larger than the wake of the model, then the wake of the ship is set equal to the wake of the model (Manen & Oossanen, 1988).

The correlation allowance, C_A, is a value that is added to the calculated smooth ship resistance coefficient in order to find the actual ship resistance. The value is a catch-all term that is often used to account for the full-scale roughness of the ship (due to welds, paint, fouling etc.), to account for differences in predicted effective power caused by using different extrapolation methods and to account for scale effects not otherwise considered (Manen & Oossanen, 1988). The ITTC 1978 method uses an equation to estimate the correlation allowance that is based on expected roughness of the ship, $C_A = \left[105\left(\frac{k_S}{L}\right)^{1/3} - 0.64\right]10^{-3}$. However, in practice the correlation allowance is thought to be different for different tanks (Manen & Oossanen, 1988, pg.61). When model test powering predictions are validated with full-scale trials, the values chosen for the correlation allowances area examined and updated. One example of correlation allowances in use are those provided by MARIN based on the ITTC 1978 extrapolation procedure, which range from 0-0.0004 according to the length of the full-scale vessel (Manen & Oossanen, 1988, Resistance, 6.4 Table 13).

The relative rotative efficiency, η_R, is the ratio between the efficiency of the propeller when tested in self-propulsion mode or operating behind the hull and the efficiency of the propeller in open water or uniform flow. The wake behind the model causes the flow over the blade as it rotates to be different from the flow in open water, so the angle of attack is changed. The proportions of turbulent and laminar flow over the blades are different. In order to account for this, the relative rotative efficiency is applied to the predicted power and is usually in the range of 0.95-1 for twin-screw ships and 1-1.1 for single-screw ships (Manen & Oossanen, 1988, Resistance, section 4).

Individual facilities omit or vary aspects of the method according to the experience and needs of the tank; a table showing current approaches is found in the ITTC 2005 Powering Prediction Committee Report Table 5.3 by Steen, reprinted here as Table 3-1 (Bose *et al.,* 2005). Some facilities change so many aspects that they use a different method entirely. For example, not all facilities use the ITTC 1957 correlation line, some facilities use a form factor obtained using Prohaska's Method (Harvald, 1983) and others do not use a form factor. Also, most facilities use a correlation allowance, but not always the same kind and a roughness correction is not always included in the correlation allowance used.

Table 3-1 Compilation of extrapolation methods in use at the organisations represented on the committee (Question marks indicate that the information was not available) (Bose *et al.*, 2005, Table 5.3)

Org	Form factor	Wind resist.	Bilge keels	Wake scaling	K_T, K_Q scaling	Prop-ulsion analysis	Roughness correction	Friction line	Blockage corr'n	Correlation allowance
A	k=0	Calc.'d	Calc. Frictional resistance	Tanaka Sasajima	ITTC'78	Thrust identity	DC_F=0.00035-Ls*2E-6	ITTC'57	?	C_A=DC_F
B	k=0	Calc.'d	?	Tanaka Sasajima	ITTC'78	Thrust identity	DC_F=0.00035-Ls*2E-6	ITTC'57	?	C_P, C_N
C	Empir Form.	Calc.'d	Calc. Frictional resistance	Tanaka Sasajima	No	Thrust identity		ITTC'57	Scott's formula	C_A
D	k=0	Calc.'d	?	Tanaka Sasajima	ITTC'78	Thrust identity	No, included in C_A	ITTC'57	No	C_A=DC_F+statistics
E	Fine ships: k=0 Full ships: k=0	Calc.'d	Tests are performed with bilge keels which are considered as part of the hull.	empirical	Run POW tests at two revs, one for prop. Test and one for predict-ion	Thrust identity	own empirical relation	Fine ships: Prandtl-Schlichting Full ships: Hughes	No	Wake and roughness allowance
F	k=0	Calc.'d	Estimated, based on experience data	Yasaki	Lerbs-Meyne (1972)	Thrust identity	Included in C_A	ITTC'57	Yes	C_A= f(L_{PP},C_B)
G	Fine ships: k=0 Full ships: k=0	Fine ships: incl. in C_R Full ships: Calcu-lated	?	Tanaka Sasajima	No?	Thrust identity	ITTC'78 (only full ships)	ITTC'57	?	C_A
H	k found by Proh-aska's meth-od	Calc.'d	Wetted surface of bilge keels added for full scale	Tanaka Sasajima	ITTC'78	Thrust identity	ITTC'78	ITTC'57	?	C_P, C_N (ITTC'78)

Past ITTC committees have completed uncertainty analyses of the tests (e.g. bias error on measurements of thrust and torque) used to provide data for the ITTC 1978 method, however a full uncertainty and sensitivity analysis of the method itself was not completed prior to this work. The question of how uncertainties in the various measured values when extrapolated to full-scale values, affect the uncertainty of the predicted power, was the aim of this work. For example, does uncertainty in thrust result in a proportional uncertainty in the final predicted power or is the predicted power overly sensitive or insensitive to this measured value? Also, it is not clear how the various propulsion factors and uncertainties in the frictional line impact the uncertainty in the predicted power. The frictional resistance coefficient, the form factor, the correlation allowance, the model and ship wake fractions, the thrust deduction fraction and relative rotative efficiency are all values that are potentially subject to the interpretation of the analyst, are site specific or due to the data used to develop the equation to calculate the factor or coefficient (e.g. turbulent flat plate friction line) have uncertainty. The frictional resistance coefficient value can be different depending on the choice of coefficient e.g. the ITTC 1957 line or the Grigson line because the equations used to calculate the coefficient are different. The thrust deduction fraction and wake fraction are usually taken from the model data that represent the operating speed. The values of w_{TS} and t in a model test series can vary by more than 10% over the test speed range and are subject to additional uncertainty due to uncertainty in the measured values used to calculate these factors. The wake is also affected by scaling from model to full-scale wake. The correlation allowance is often based on a database of collected validated model data at the testing facility and can be subject to an uncertainty range. Due to the possibility of variation in these propulsion factors it is likely that tests performed at different facilities even using the same extrapolation procedure would result in different predicted powers.

Indeed, a 1996 study found that for one proposed vessel the predictions of power from 13 shipyards differed by 36% from highest to lowest power and for another vessel the predictions from 4 test basins and one consultant differed in power by 40% for the same service speed (Anon., 1996).

3.1 Method of Uncertainty Analysis

The ITTC 1978 method was analysed in steps using Monte Carlo simulation. First the physical test results were varied by a standard deviation in a normal distribution and then the propulsion factors and frictional coefficient were varied by a standard deviation in a normal distribution. All the output results were presented in graphical and tabular forms and showed the standard deviation as a percentage of the output mean.

By using Monte Carlo simulation with pre-determined standard deviations applied to the inputs, it is possible to see how a representative variation in an input value will affect the resulting powering prediction when that variation is propagated through the ITTC 1978 method. The simulation is used here to vary a set of individual inputs and show the impact that individual factors have on the predicted power and also it is used to vary a selection of combined inputs. The standard deviation applied is an artificial value used to perform a primarily qualitative analysis, it is intended to represent the potential error in model data from for example, testing equipment, human error, differences between test basins and size of model errors.

The first set of inputs that was varied was the propeller open water test data set. The propeller advance coefficient and thrust and torque coefficients of the test were varied individually and together by a 1% standard deviation to determine if this amount of variation amplified the final uncertainty in the delivered power or was propagated through the method to result in a 1% or less standard deviation in the power. The resistance and self-propulsion test results were similarly varied.

Once each of the tests was investigated alone, the variation was applied to all the test inputs together to determine how a 1% variation in all measured values influenced the uncertainty in the delivered power.

Table 3-2 Model ship test data

Chart Legend	Ship Type	# of Props	Ship Speed m/s	Thrust Deduction Fraction	Model Wake	Ship Wake
Ship #1	Chemical Carrier	1	7.36	0.196	0.326	0.266
Ship #2	Chemical Carrier	2	7.36	0.193	0.168	0.180
Ship #3	Chemical Carrier	1	7.36	0.203	0.285	0.250
Ship #4	Passenger	2	13.37	0.197	0.123	0.160
Ship #5	RoRo Ferry	2	12.34	0.177	0.122	0.146
Ship #6	Ferry	2	11.83	0.247	0.081	0.162
Ship #7	Passenger Cruise Liner	2	10.28	0.172	0.147	0.157
Ship #8	Ferry	1	5.66	0.149	0.312	0.249
Ship #9	Car Passenger Ferry	2	13.37	0.187	0.105	0.144
Ship #10	Passenger	2	9.77	0.315	0.038	0.170
Ship #11	Cruise Liner	2	11.06	0.264	0.077	0.169
Ship #12	Passenger	2	11.32	0.226	0.075	0.146
Ship #13	Passenger	2	11.06	0.143	0.096	0.118
Ship #14	Passenger	2	8.49	0.214	0.174	0.190
Ship #15	Cruise Vessel	2	10.8	0.200	0.075	0.134
Ship #16	Passenger Cruise Liner	2	12.35	0.185	0.154	0.167
Ship #17	Container Ship	1	8.22	0.229	0.532	0.374
Ship #18	Container Ship	1	8.22	0.300	0.586	0.443
Ship #19	Tanker	1	8.74	0.179	0.387	0.280
Ship #20	Tanker	1	8.48	0.193	0.505	1.778
Ship #21	R-Class Icebreaker	2	8.75	0.329	0.063	0.185

Next the frictional coefficient and propulsion factors were varied by a standard deviation that was determined to be a representative value but not necessarily 1%. Each of the propulsion factors and the coefficient of friction were investigated individually and then all the propulsion factors and the frictional coefficient were varied together and with the measured test values.

The final picture that was created with the different results shows how the predicted delivered power was impacted by changes in parameters, which are subject to quantifiable uncertainty, that are integral to the method.

The designated ITTC 2005 database of ship model tests and corresponding trials presented in the powering prediction committee report and in Chapter 2 were used in the simulations (Bose *et al.*, 2005).

A selection of the available data was used and a summary description of the data chosen is in Table 3-2. This table is also a legend corresponding to the succeeding plots.

The data for ship #21 was originally load-varying, however the remaining data in the set are non-load varying or continental method test results (Spencer *et al.*, 1992, Bose *et al.*, 2005) so the data for ship #21 were simulated as non-load varying and then input to the program in the same manner as the continental method test results.

3.2 Variation of Measured Test Data

3.2.1 Variation of All Measured Inputs

All the measured input values, Table 3-3, were varied by a standard deviation of 1% of the maximum value in the file, e.g. velocity in the resistance test, V_R, from 0-1.5m/s had a standard deviation of 0.015, 1% of 1.5m/s. The simulation was run with variation in all of the measured values together, Figure 3-1.

Table 3-3 Measured Value Inputs

Tests	Parameters varied	% Standard Deviation
Self-propulsion test	V_M, n_M, T_M, Q_M, F_D	1%
Resistance Test	R_{TM}, V_R	1%
Propeller open water test	K_T, K_Q, J	1%

To simplify the analysis and allow observation of the effect of different inputs and other factors on the prediction of power with limited interaction between factors, some factors were set to neutral values for the initial sets of simulations, values that did not affect the predicted full-scale results. The form factor was set to zero, as was the correlation allowance, and the relative rotative efficiency was set to 100%.

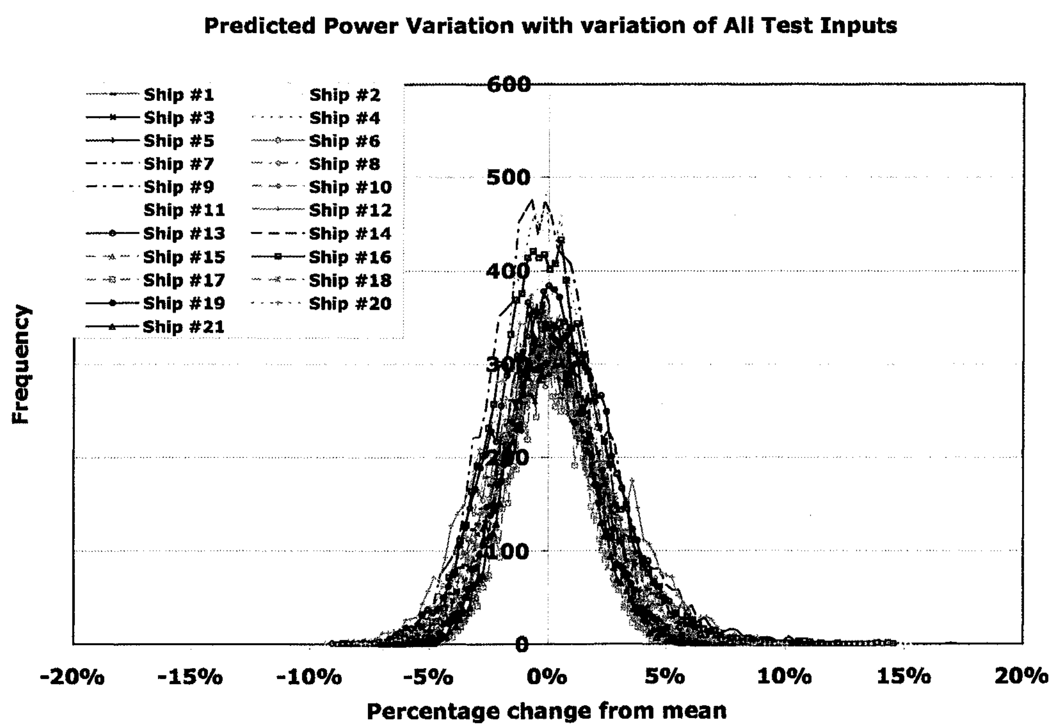

Figure 3-1 Predicted power variation when all measured test values varied

The predicted delivered power of all the ships fell over a normally distributed range with standard deviations in the predicted power in the range 1.6%-2.6% (Table 3-4). There was a slight skew in the positive direction, which was due to the resistance and is explained in detail in section 3.2.3. Predicted power refers to predicted delivered power here.

Table 3-4 Comparison of Standard Deviations – measured values varied together

Ship #1	1.01%	1.42%	2.28%	3.04%	1.77%	0.00%	5.11%
Ship #2	1.00%	1.19%	1.88%	2.31%	1.47%	1.47%	4.57%
Ship #3	0.99%	1.01%	2.00%	2.90%	1.53%	0.00%	4.12%
Ship #4	1.00%	1.55%	1.90%	3.37%	1.30%	1.30%	6.63%
Ship #5	0.99%	1.30%	1.91%	2.18%	1.81%	1.81%	5.24%
Ship #6	1.00%	1.26%	2.01%	3.03%	1.49%	1.49%	5.85%
Ship #7	1.00%	1.05%	1.81%	2.28%	1.50%	1.50%	5.07%
Ship #8	1.00%	1.41%	2.56%	4.30%	1.46%	0.00%	7.15%
Ship #9	1.00%	1.52%	2.60%	2.19%	1.72%	1.72%	5.50%
Ship #10	0.99%	1.15%	2.29%	1.55%	2.23%	2.23%	4.56%
Ship #11	1.00%	1.49%	2.19%	2.03%	1.78%	1.78%	5.57%
Ship #12	1.00%	1.48%	2.52%	1.97%	2.13%	2.13%	5.45%
Ship #13	1.01%	1.37%	2.39%	2.01%	2.09%	2.09%	5.14%
Ship #14	1.00%	1.17%	1.89%	2.62%	1.55%	1.55%	5.91%
Ship #15	0.99%	1.21%	1.96%	2.48%	1.59%	1.59%	5.12%
Ship #16	1.00%	1.57%	2.35%	2.81%	1.49%	1.49%	6.16%
Ship #17	1.00%	0.67%	1.63%	7.56%	1.52%	0.00%	4.14%
Ship #18	1.00%	0.84%	1.65%	7.11%	1.44%	0.00%	4.36%
Ship #19	1.00%	1.06%	1.86%	5.08%	1.80%	0.00%	4.95%
Ship #20	1.00%	0.92%	2.24%	5.13%	2.41%	0.00%	4.16%
Ship #21	0.99%	1.01%	1.72%	2.26%	0.91%	0.91%	4.91%

A 1% standard deviation in all of the measured test data caused an average of 2.1% standard deviation in the predicted power of all the ships in Figure 3-1. For a normal distribution the standard deviation can be used as a 68% confidence limit and 1.96 x standard deviation as a 95% confidence limit (Taylor, 1997). This means the probability that the predicted power result lies in the range of +/- 1.96 x standard deviations around the mean result is 95%, or that to have 95% confidence in the result the range of uncertainty about the mean is ± 1.96 x standard deviation.

The standard deviation of the predicted power is an average of 2.1% and to have 95% confidence in the result the uncertainty would be ± 4.1%. Over the range of ships this uncertainty would be a minimum of 1.63 x 1.96 = 3.2% and a maximum of 2.6 x 1.96 = 5.1%. With repeated and replicated tests the uncertainty of the results can be reduced. However, this can be challenging with ship model testing, as tank time is expensive and trade offs need to be carefully considered, reliability of the prediction method becomes even more essential.

Three ship data sets were run at different percentage standard deviations to determine if the variation was linear. The ships were run with variation in the measured test values from the three tests. It was clear from the variations, Figure 3-2-Figure 3-4, that applying 0.5% standard deviation to the measured test values resulted in approximately half the standard deviation in predicted power of applying 1% standard deviation and one third of applying 1.5% standard deviation, Table 3-5.

Table 3-5 Comparison of standard deviation in predicted power with change in input (measured) value standard deviation

Ship	[illegible]	[illegible]	[illegible]
Ship #1	1.12%	2.28%	3.40%
Ship #9	1.26%	2.60%	4.04%
Ship #16	1.13%	2.35%	3.57%
Ship #21	0.88%	1.72%	2.61%
Average	**1.10%**	**2.24%**	**3.40%**

The method of variation was found to be stable within a restricted range of standard deviation. When standard deviations above ~2% were tested, the measured values were increased or decreased by amounts that in some of the iterations caused the input data to be shifted to such a degree that is was not possible to find an intersection between the curves used to determine the propeller operating point (see chapter 2) or the value was unrealistic. In these cases the program was unable to return a final full-scale result. These types of results would not occur in the analysis of test data using a manual method by a skilled analyst because such problems with the data would be recognised.

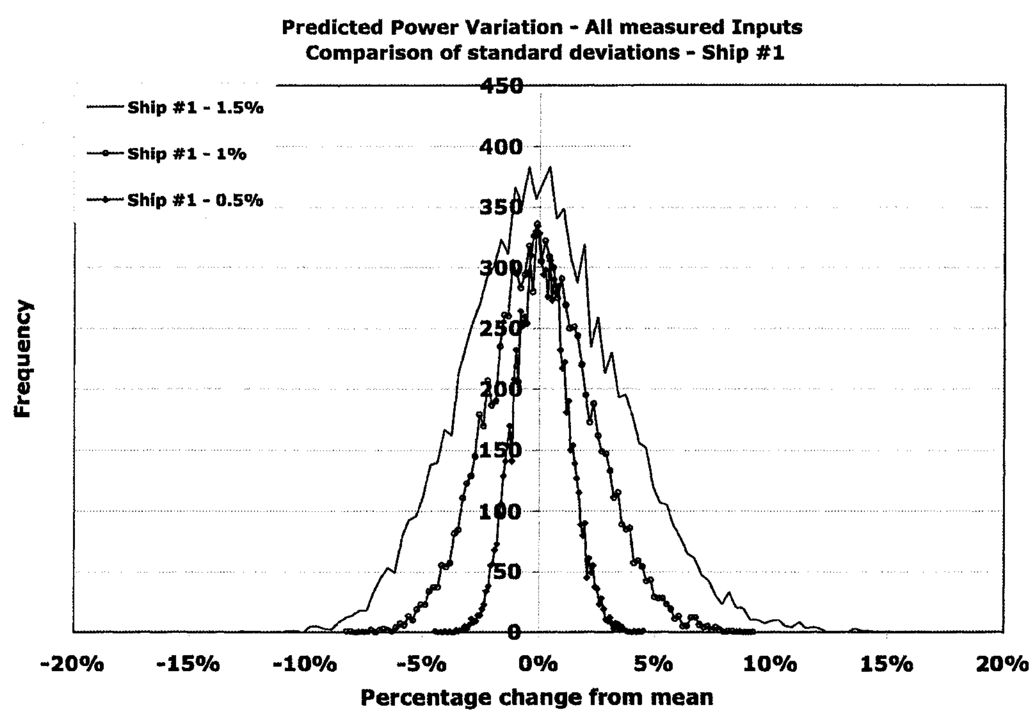

Figure 3-2 Results of varying the amount standard deviation of the measured test values, Ship #1

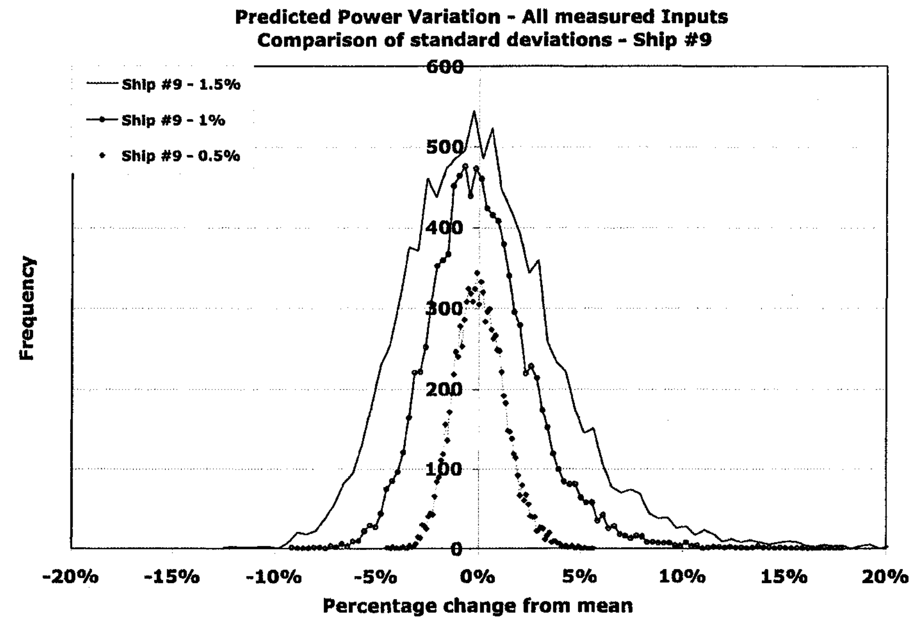

Figure 3-3 Results of varying the amount standard deviation of the measured test values, Ship #9

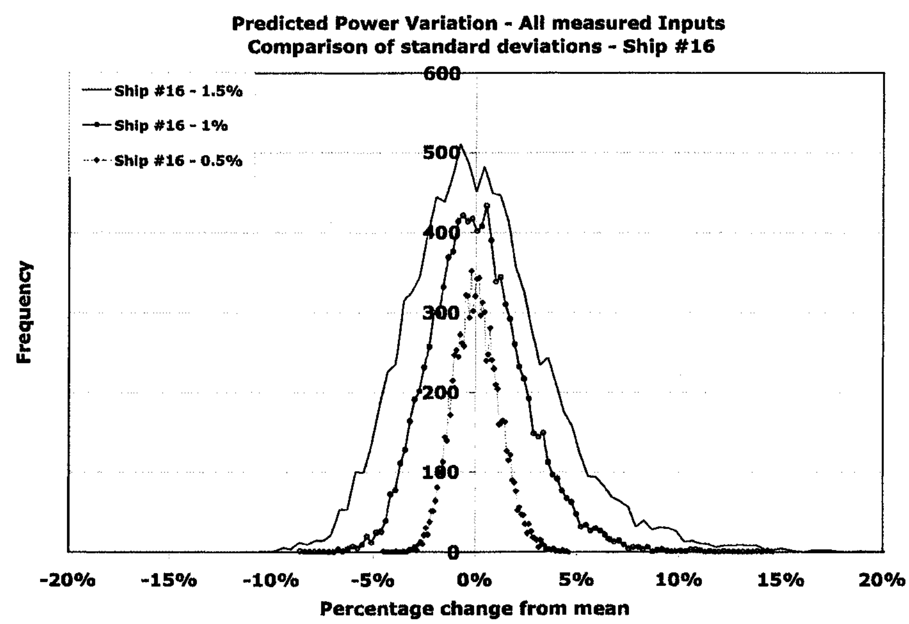

Figure 3-4 Results of varying the amount standard deviation of the measured test values, Ship #16

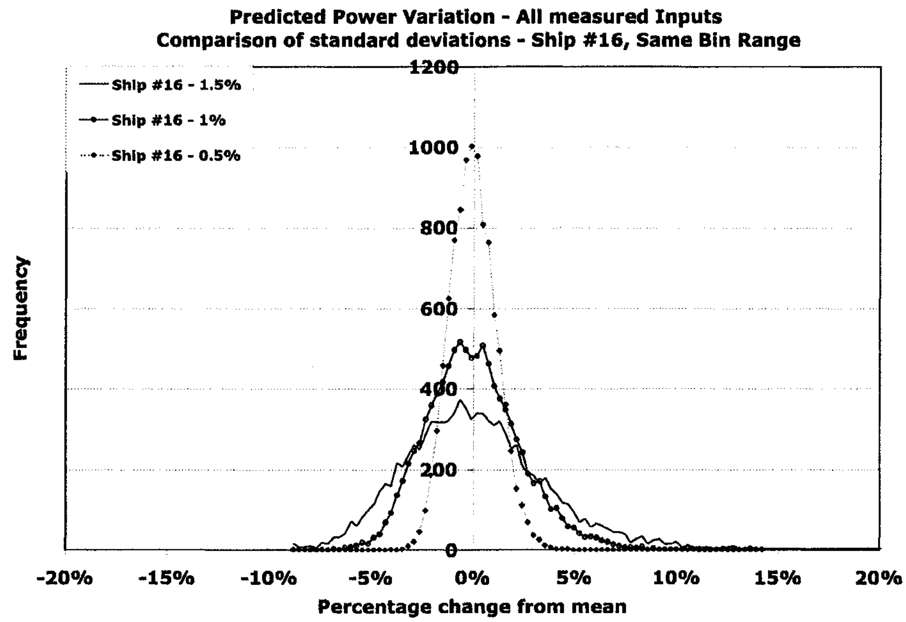

Figure 3-5 Variation in predicted power distribution for input standard deviation values of 0.5%, 1% and 1.5% when the bin range was kept constant for one ship.

The integrated area under the curve in the plots throughout this thesis is always 100%; the bin ranges for the histograms can sometimes make the plots appear as if there is a difference in the integrated area when different distributions are plotted together. The plots are all shown as a percentage change in power from the mean. The purpose of presenting the data in this manner was to allow the different ship powering predictions to be compared directly; the predicted power of the ship model data sets ranged from less than 600 kW to over 42000 kW. The bin ranges for the histograms of the power were chosen to give an even distribution of points from the minimum to the maximum value and were different for each data set. Using ship #16 to illustrate, if the bin ranges were chosen manually and kept constant then the change in predicted power with change in input standard deviation for ship #16 clearly showed equal areas under the curve of the distribution, Figure 3-5.

Table 3-6 Comparison of predicted power standard deviation with and without relative rotative efficiency calculated within the ITTC 1978 method

	$\eta_R = 100\%$	η_R - *calculated*
Ship #1	2.28%	1.75%
Ship #9	2.60%	2.24%
Ship #12	2.52%	2.10%
Ship #16	2.35%	1.44%
Ship #17	1.63%	1.42%
Ship #21	1.72%	1.75%

The relative rotative efficiency was assigned a value of 100% in the first phase of analysis and then the predicted power calculation was compared to the predicted power using the same variations in the input values, frictional coefficient and propulsion factors but with the relative rotative efficiency calculated within the method (see section 3.3.7). The standard deviation of the predicted power was reduced by 0.4%.

The standard deviation of 'all inputs' included standard deviation of the measured values of the propeller open water test, the resistance test and the self-propulsion test, Table 3-3. The next step was to determine which if any of the model tests contributed most significantly to the uncertainty in the predicted power and which test had the least impact. After these three runs, the individual measured values were varied alone (thrust, torque etc.) to determine the effect each measured value from the test series had on the predicted power.

3.2.2 Variation of Propeller Open Water Test Inputs

The program was run with parameters from the propeller open water test varied. A subset of ships was used for this more detailed analysis, the highlighted ships in Table 3-2. The values varied were the advance coefficient and the thrust and torque coefficients, Table 3-3. The standard deviation of each value was 1% of the maximum value in the file.

When the results from the propeller open water tests were varied alone, there was an average reduction of 0.9% in predicted power standard deviation from the average 'all test inputs' standard deviation over the ships in the subset, Table 3-7 and Table 3-4. A direct comparison of predicted power standard deviations is provided in Table 3-11.

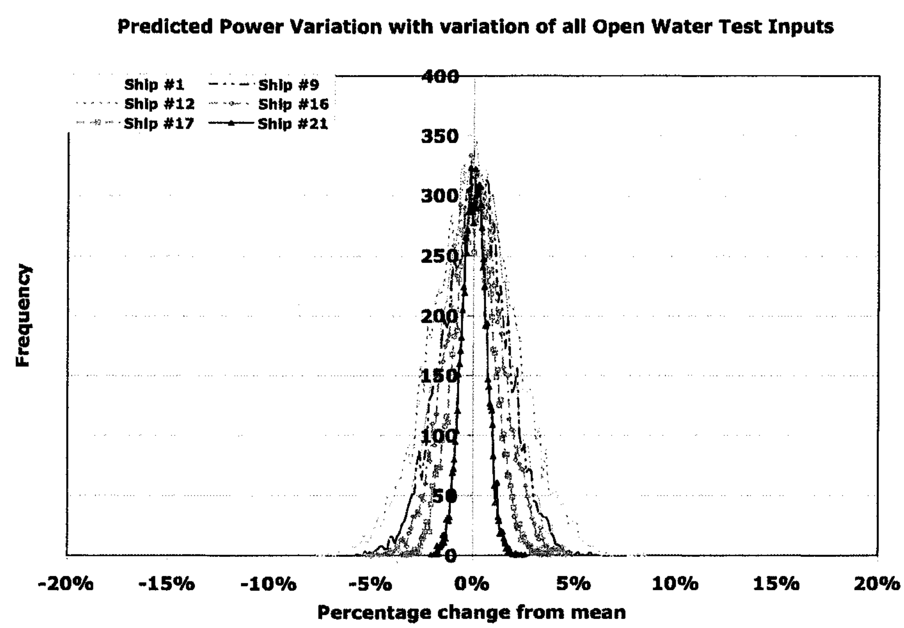

Figure 3-6 Predicted power distribution when all propeller open water test values varied

The resulting standard deviation in predicted power ranged from 0.59-2.12%. This translates into an average uncertainty of approximately 2.69% for 95% confidence. The range of uncertainty is large and this is attributed to the number of test points in the propeller open water data sets provided. The propeller open water test values are used to define a regression curve that is input to the program. When there are few points on the curve (< 8) the regression is subject to greater uncertainty than when there are many (>45). This greater change lead to a larger standard deviation for the predicted power for some ships, the Ship#21 data set was the only set with a large number of points defining the propeller open water performance and the power predicted had the smallest standard deviation. When the randomising program was run with only 11 points in the propeller open water input file for ship #21 (J = 0, 0.16, 0.24, 0.30, 0.44, 0.52, 0.60, 0.70, 0.78, 0.84, 0.88) the resulting predicted power standard deviation was 1.22% compared to 0.59% when the file had 45 points, clearly showing that the extra runs during testing reduce the uncertainty in the predicted power. In a testing series this could be addressed by using a well-tested stock propeller for the self-propulsion test.

Table 3-7 Comparison of Standard Deviations – Propeller Open Water

Ship #1	0.00%	0.20%	1.57%	0.60%	1.46%	0.00%	0.00%
Ship #9	0.00%	0.20%	1.60%	0.29%	1.48%	1.48%	0.00%
Ship #12	0.00%	0.23%	2.12%	0.51%	2.01%	2.01%	0.00%
Ship #16	0.00%	0.18%	1.36%	0.34%	1.25%	1.25%	0.00%
Ship #17	0.00%	0.22%	1.01%	1.48%	0.87%	0.00%	0.00%
Ship #21	0.00%	0.08%	0.59%	0.19%	0.54%	0.54%	0.00%

When there is a 0% standard deviation of a parameter in the tables listing the predicted standard deviations this means that that full-scale parameter was not varied through the variation of the input being studied, i.e. if the open water test data is varied alone, the ship velocity and the effective power are not varied because the open water data is not used to calculate these parameters, Table 3-7. For consistency, all the tables listed the seven full-scale parameters regardless of whether the parameter had a standard deviation.

3.2.3 Variation of Resistance Test Inputs

The simulation was next run with only the values from the resistance test varied, the measured resistance and the velocity of the carriage.

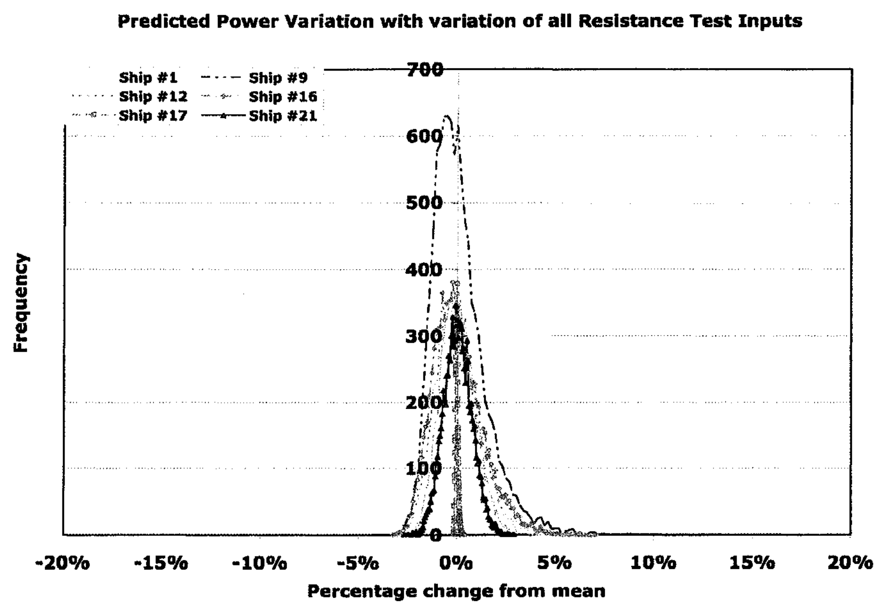

Figure 3-7 Predicted power variation when resistance test values varied

The data for ship#9 was different to the other data sets because it had a higher number of data points in the mid range of the distribution curve. The resistance data for ship#9 had the smallest speed range (2.35-2.66m/s) and had the highest velocities of all the ships, Figure 3-8.

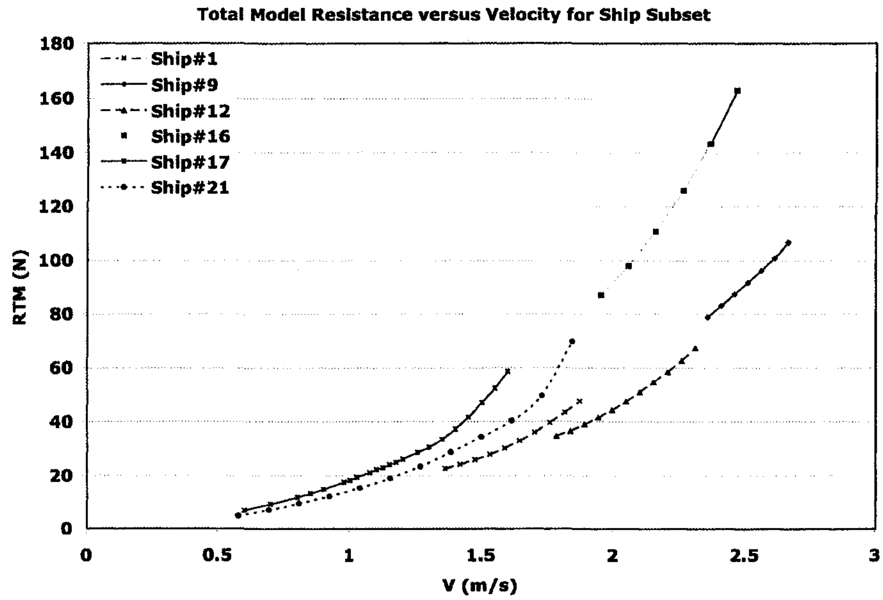

Figure 3-8 Resistance versus Velocity for ship data subset

When the resistance data of a model ship was varied by 1% of the maximum value in the file, the range of resistance values below the maximum were varied by greater than 1% of the value. For example, if the maximum resistance in a file was 80N, then the 1% standard deviation was 0.8N so all the values 0N-79N were varied by a standard deviation of 0.8N, greater than 1% of the value. The 1% (0.0266) value used as the standard deviation of the velocity in the file for ship #9 is close to 1% of each of the velocity values in the resistance input file (ranging from ~2.3-2.6m/s). This means the input regression curve representing the resistance was varied less for each iteration than the other ships and this reduced the spread of the predicted power distribution.

The power distributions produced when the resistance data was varied are all skewed high. The curves of the resistance test data are shown in Figure 3-8. The data used to produce the resistance curve of the ship were randomised before the regression curve was calculated using least squares estimation, i.e. the resistance value determined to represent the drag on the vessel at the chosen speed was varied before the regression curve was determined. The resistance and velocity values that were extrapolated in the powering prediction method were those that corresponded to the operating speed of the full-scale vessel and these values were all found among the higher values of the input data and on the steepest portion of the polynomial used (see Figure 3-8).

Table 3-8 Example of predicted power with varied resistance test data

Bin	*Frequency*	*Cumulative %*
34400	0	.00%
34600	15	.15%
34800	148	1.63%
35000	605	7.68%
35200	1280	20.48%
35400	1801	38.49%
35600	1865	57.14%
35800	1510	72.24%
36000	1130	83.54%
36200	703	90.57%
36400	412	94.69%
36600	259	97.28%
36800	135	98.63%
37000	71	99.34%
37200	37	99.71%
37400	16	99.87%
37600	6	99.93%
37800	5	99.98%
38000	0	99.98%
38200	2	100.00%

This means that due to the nature of the curve profile, when the data was varied (using Monte Carlo simulation) below the operating speed the data was varied through a small range of the low resistance values and when the data was varied above the operating speed the extent of the values of high resistance values was larger in comparison. Also, because higher resistance means higher power, this led to the skewing of predicted power above the mean.

A sample of the predicted powers is included in Table 3-8. Had the resistance value determined for the operating speed been varied after it was input to the program the data would have been more evenly distributed, however, it would not have fully represented the potential change in predicted power due to uncertainty in the resistance test results.

Table 3-9 Comparison of Standard Deviations – Resistance Test

Ship #1	0.00%	0.63%	0.88%	1.26%	0.25%	0.00%	2.48%
Ship #9	0.00%	0.88%	1.37%	1.36%	0.48%	0.48%	3.53%
Ship #12	0.00%	0.86%	1.12%	1.22%	0.25%	0.25%	3.22%
Ship #16	0.00%	0.95%	1.28%	1.74%	0.32%	0.32%	4.03%
Ship #17	0.00%	0.19%	0.07%	1.61%	0.13%	0.00%	1.49%
Ship #21	0.00%	0.42%	0.72%	1.01%	0.30%	0.30%	2.43%
Average	**0.00%**	**0.66%**	**0.91%**	**1.36%**	**0.29%**	**0.34%**	**2.86%**

This result also shows that in practice the ITTC 1978 extrapolation method causes the predicted power to be more often high than low and to counter this, resistance test test-velocities should include those both above and below the operating speed of extrapolation to clearly show the trends in the data. In this analysis the speed at which the data was extrapolated (without randomisation) corresponded to a resistance value that was always within the range of the resistance test data provided but the higher randomised values were found beyond the upper limit of data used to determine the regression curve.

When the resistance values were varied alone the standard deviation of the predicted power was on average 1.37% less than the when all measured test values were varied together Table 3-9 and Table 3-11. The standard deviation of the predicted power when the resistance test inputs were varied ranged from 0.07 to 1.37%, an average uncertainty range of approximately 1.78% with 95% confidence. The smallest standard deviation was predicted for ship #17 which is a single screw vessel. The other single screw vessel in the set was ship #1 and the predicted power standard deviation was 0.88%. Ship #21 also had a small predicted power standard deviation and is a twin-screw vessel; the small standard deviation is attributed to the large number of points and range of velocity in the resistance data file which reduced the sensitivity of the regression curve to the applied variation (as was demonstrated with the propeller open water data), this vessel was tested as a research vessel however, and not as a commercial powering test.

3.2.4 Variation of Self Propulsion Test Inputs

The self-propulsion test measured data, Table 3-3, were varied alone and all the data sets were entered as non-load varied data.

The predicted power had similar standard deviation for all the ships in the data set, Figure 3-9, showing a very consistent effect of variation in the self-propulsion test inputs.

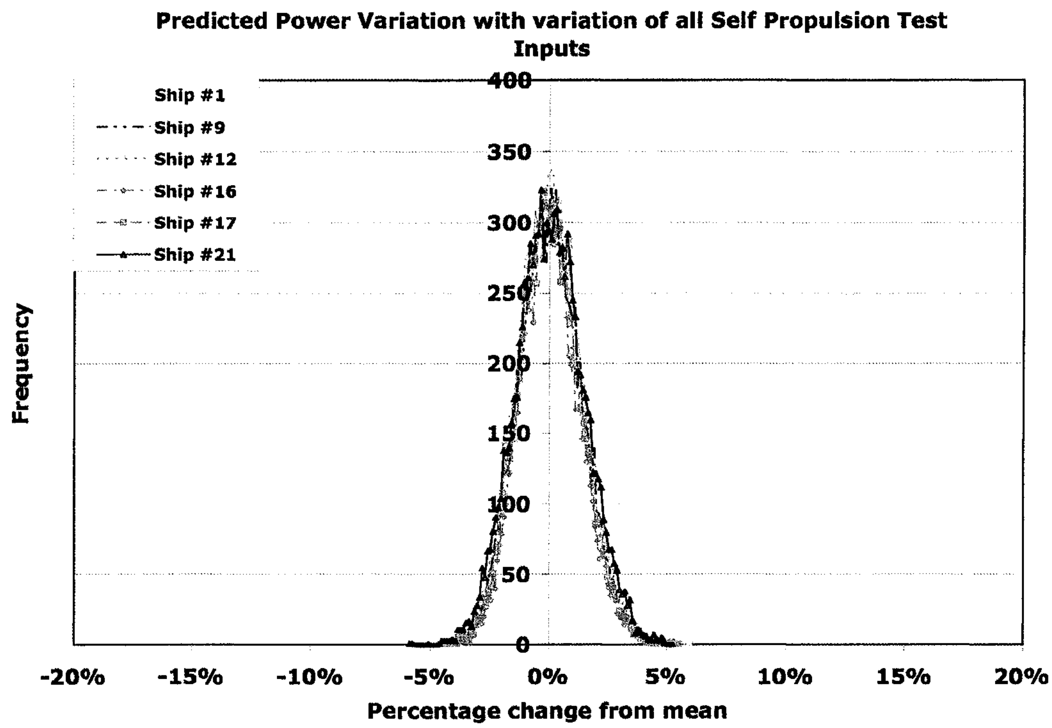

Figure 3-9 Predicted Power distributions when inputs to self-propulsion test are varied

The standard deviation in the predicted power varied from 1.28% to 1.46%, Table 3-10 and Table 3-11, resulting in an uncertainty of on average 2.66% with 95% confidence. The consistency and conformity of the data is attributed to the variation of only one point, i.e. one value of shaft speed is varied, one value of thrust, one torque value, one shaft speed and one tow force value per ship. Using the regression curves of the propeller open water data and the resistance data as data inputs adds a further source of non-uniformity because these curves can be centered above or below the self-propulsion test self-propulsion point. For example, the curves presented in Figure 3-8 were used to show that resistance data that is input to the powering prediction method can be highly varied in range and scope and this leads to a greater range of variation in the predicted power than one self-propulsion data point.

Table 3-10 Comparison of Standard Deviations – Self Propulsion Test

Ship #1	1.01%	1.27%	1.37%	2.75%	0.92%	0.00%	4.51%
Ship #9	0.99%	1.16%	1.35%	1.63%	0.66%	0.66%	3.95%
Ship #12	1.01%	1.40%	1.36%	1.82%	0.75%	0.75%	4.60%
Ship #16	1.01%	1.20%	1.28%	2.12%	0.58%	0.58%	4.63%
Ship #17	1.00%	0.60%	1.32%	7.26%	1.29%	0.00%	3.95%
Ship #21	0.98%	0.91%	1.46%	2.00%	0.68%	0.68%	4.25%

3.2.5 Comparison of Tests

When the standard deviations of the predicted power due to standard deviation of each test alone were compared (Table 3-11) it was clear that the resistance test had the least impact on the overall uncertainty compared to when the three tests were varied together.

Table 3-11 Comparison of predicted power standard deviations – all tests

	SP	OW	Res	All Inputs
Ship #1	1.37%	1.57%	0.88%	2.28%
Ship #9	1.35%	1.60%	1.37%	1.88%
Ship #12	1.36%	2.12%	1.12%	2.00%
Ship #16	1.28%	1.36%	1.28%	1.90%
Ship #17	1.32%	1.01%	0.07%	1.91%
Ship #21	1.46%	0.59%	0.72%	2.01%
Average	**1.36%**	**1.37%**	**0.91%**	**2.22%**

The uncertainty in the propeller open water and self-propulsion test data had on average quantitatively similar influence on the variation in the predicted power.

3.2.6 Variation of Individual Measured Values

The influence of individual test measurements was examined next. In each run of the simulations one of the measured parameters was varied while the others remained constant.

Propeller Open Water Test Results

The standard deviation in overall predicted power that resulted when the propeller open water test parameters were varied individually was small and the distributions are shown in Figure 3-10, Figure 3-11 and Figure 3-12.

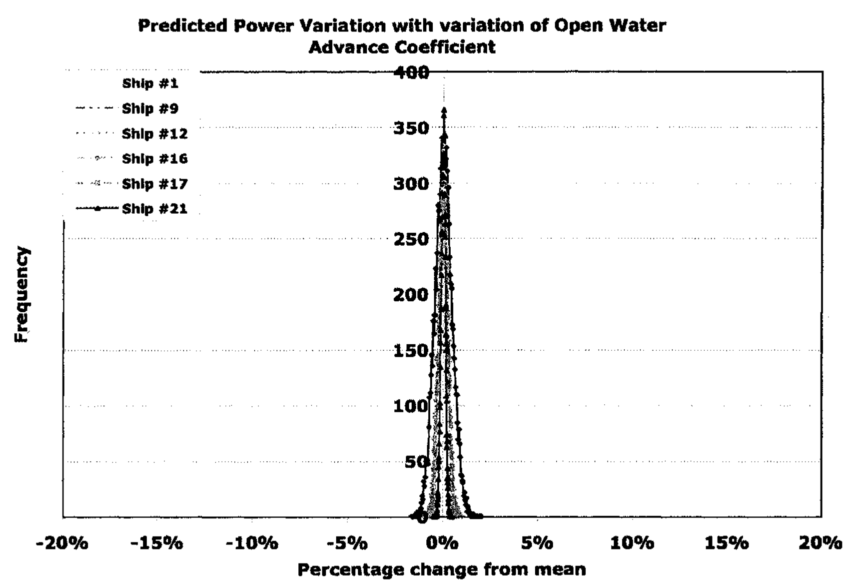

Figure 3-10 Distribution of predicted power when *J* is varied

The average standard deviation of the predicted power was 0.21% when the advance coefficient was varied with a 1% standard deviation, Figure 3-10, 1.00% when the thrust coefficient was varied by 1%, (Figure 3-11) and 0.66% when the torque coefficient was varied by 1%, (Figure 3-12, Table 3-12). Therefore the predicted power is very dependent on the thrust coefficient from the open water test.

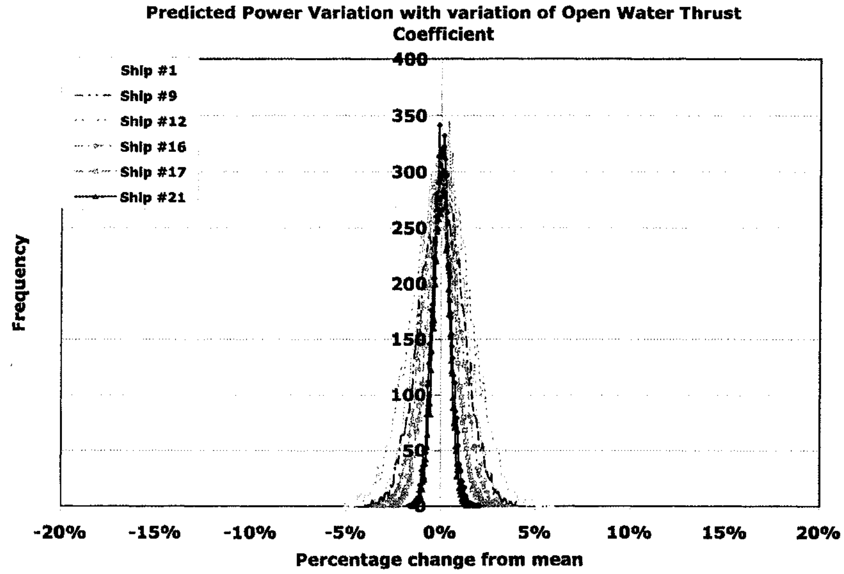

Figure 3-11 Distribution of predicted power when K_T is varied

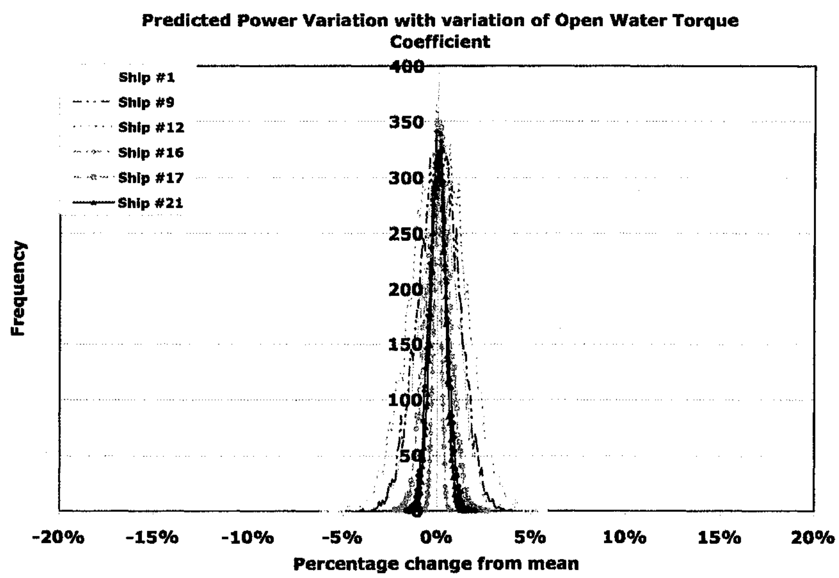

Figure 3-12 Distribution of predicted power when K_Q is varied

The variation in the predicted power when any of the test parameters are varied alone is small but noticeable and it has previously been shown that the uncertainties in the propeller open water test results contribute together to an overall average standard deviation of 1.37% or an uncertainty of 2.7% in predicted power, Table 3-11.

Resistance Test Results

The resistance test velocity and resistance data were individually varied by a standard deviation of 1% and the average predicted standard deviations in power were 0.86% and 0.32% respectively. Figure 3-13 and Figure 3-14 show the variation in power for the subset of ships.

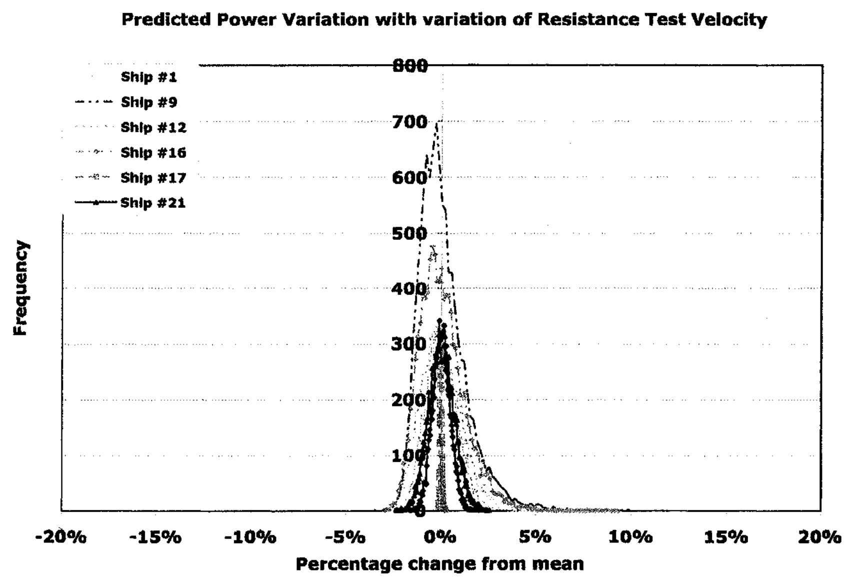

Figure 3-13 Comparison of variation in predicted power when resistance test velocity is varied

Again the standard deviation in predicted power is small and it is clear that although uncertainty in the resistance test results can cause the predicted power to skew high (pg.

3.19), the ITTC 1978 prediction method is relatively stable with respect to the resistance test.

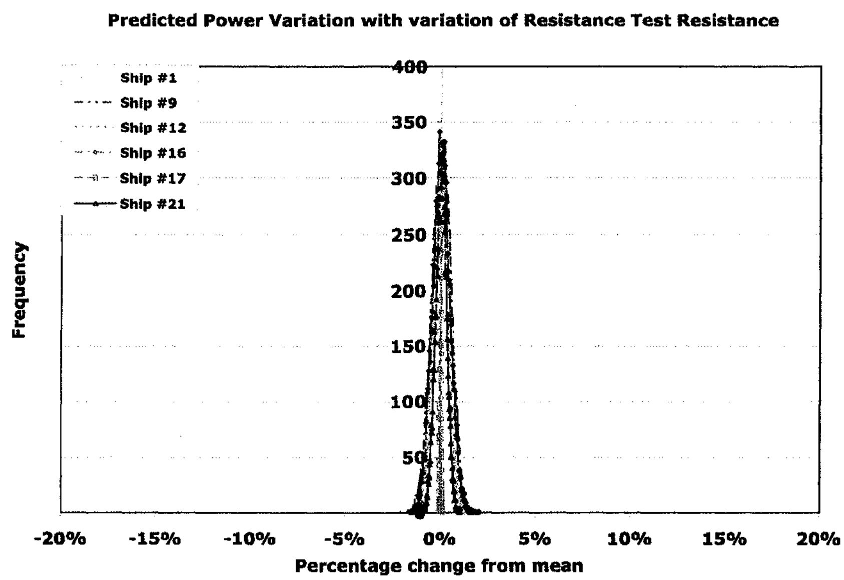

Figure 3-14 Comparison of variation in predicted power when resistance test resistance is varied

Self Propulsion Test Results

The five measured parameters of the self-propulsion test were each varied alone. The values were varied by a 1% standard deviation and the standard deviation of the predicted power ranged on average from 0.38% to 0.89% (Table 3-12, Figure 3-15-Figure 3-19). Each power that was predicted when the self-propulsion test velocity (Figure 3-15), and the self-propulsion test torque (Figure 3-19), had a 1% standard deviation resulted in an average standard deviation of 0.89%. The measured value from the self-propulsion test that caused the smallest standard deviation in predicted power was the tow force; it resulted in an average predicted power standard deviation of 0.38% (Figure 3-18).

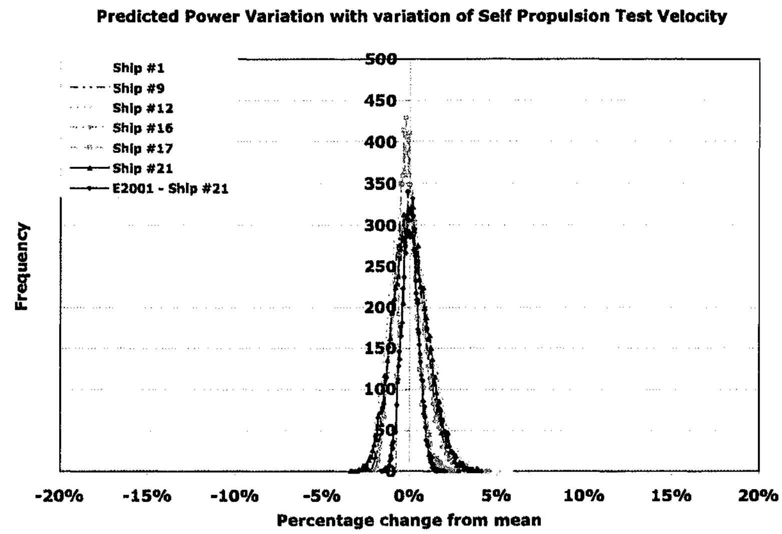

Figure 3-15 Comparison of predicted power variation when self-propulsion test velocity is varied

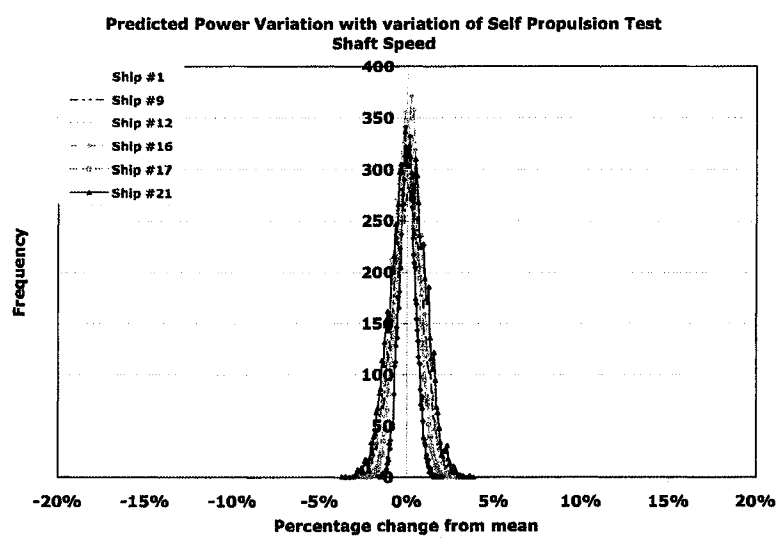

Figure 3-16 Comparison of predicted power distributions when self-propulsion test shaft speed is varied

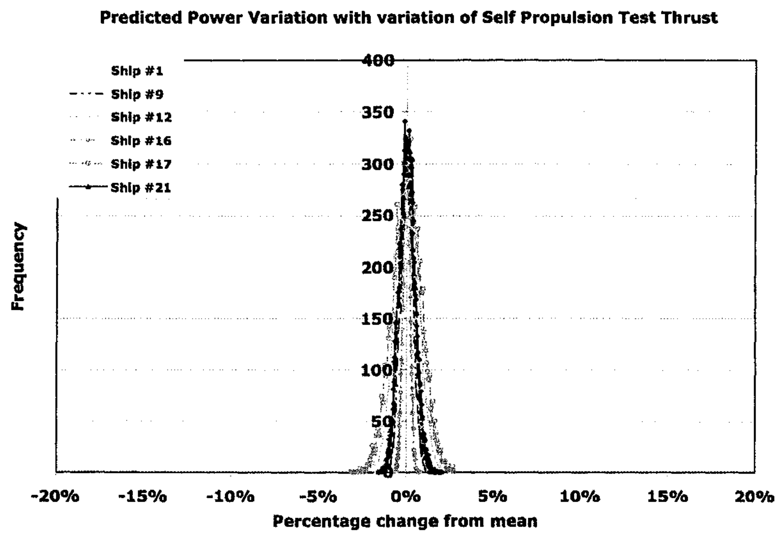

Figure 3-17 Comparison of predicted power variation when self-propulsion test thrust is varied

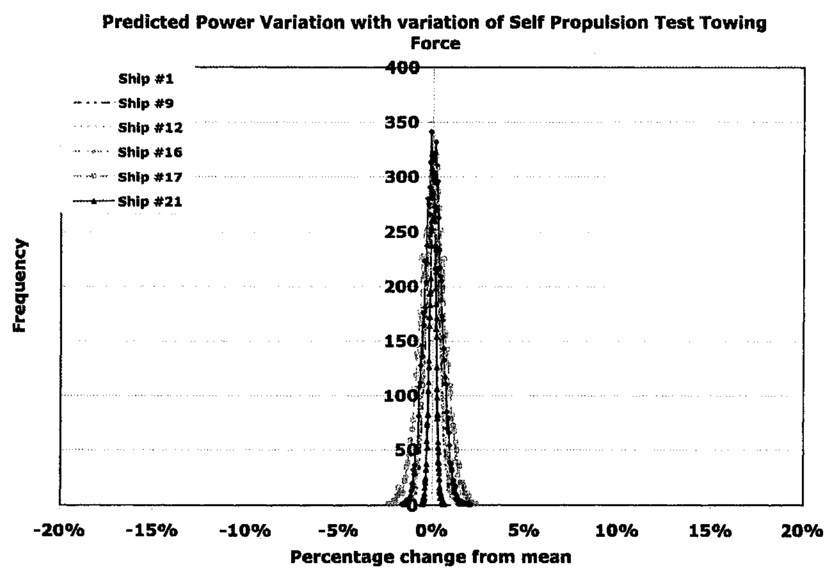

Figure 3-18 Comparison of predicted power variation when self-propulsion test tow force is varied.

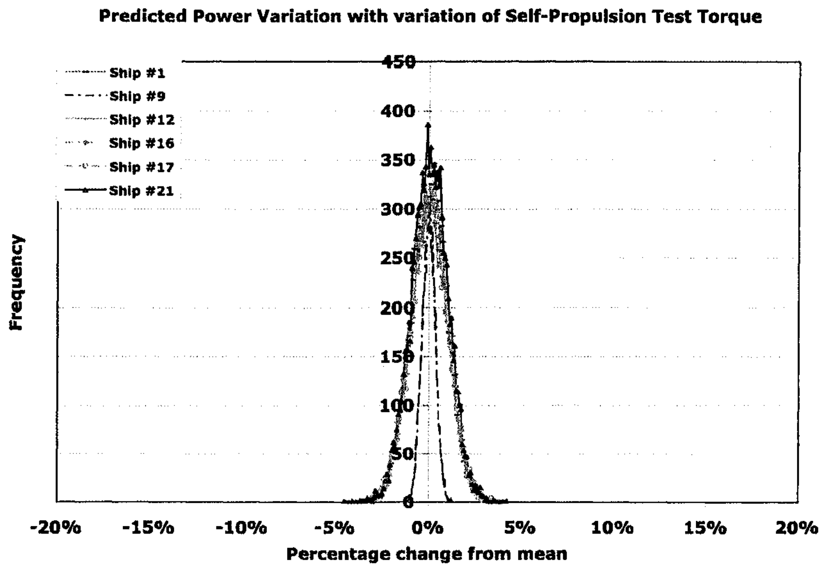

Figure 3-19 Comparison of predicted power variation when self-propulsion test torque is varied.

Table 3-12 Comparison of resulting predicted power standard deviations when individual test values were varied

	Self Propulsion Test					Propeller open Water Test			Resistance Test	
	V	n	F_D	T	Q^*	J	K_T	K_Q	V_R	R_M
Ship	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)	P_{DS} (kW)
Ship #1	0.93%	0.69%	0.33%	0.66%	1.00%	0.20%	1.17%	1.04%	0.84%	0.30%
Ship #9	0.92%	0.86%	0.36%	0.36%	0.36%	0.22%	1.16%	0.22%	1.29%	0.50%
Ship #12	1.12%	0.70%	0.35%	0.44%	1.00%	0.25%	1.53%	1.45%	1.07%	0.39%
Ship #16	0.88%	0.83%	0.41%	0.20%	0.99%	0.26%	0.95%	0.20%	1.22%	0.41%
Ship #17	0.49%	0.64%	0.66%	0.81%	1.00%	0.22%	0.75%	0.62%	0.06%	0.03%
Ship #21	1.02%	0.17%	0.17%	0.44%	1.00%	0.11%	0.42%	0.39%	0.68%	0.30%
Ave.	**0.89%**	**0.65%**	**0.38%**	**0.49%**	**0.89%**	**0.21%**	**1.00%**	**0.66%**	**0.86%**	**0.32%**

Individually the test results of the all of the physical tests do not have a large affect on the uncertainty in the predicted power, although any of the predicted powers in Table 3-12 that are above 1% indicate that the ITTC 1978 powering prediction method amplifies the uncertainty of that parameter for that data set. The test results show that the ITTC 1978 method is relatively stable with respect to the individual test data that is used to predict full-scale power. The combined uncertainty of the input data, which was represented by a 1% standard deviation applied to all the test inputs, resulted in a standard deviation of on average 2.1% and when a 95% confidence interval was applied, the resulting uncertainty was 1.96 standard deviations or 4.12%. This is a value that can be reduced with additional test points in the resistance and open water test programs and also through repeat tests, replicate experiments and regular calibration of equipment (Coleman and Steele, 1999). However there are other sources of uncertainty throughout the method and when the 1% standard deviation of measured values was combined with the uncertainty applied to the coefficient of friction and the propulsion factors the standard deviation of the predicted power was larger. This is outlined in the following section.

3.3 Variation of the Coefficient of Friction and Propulsion factors

"Propulsion factor" is used here as a general term to describe the factors used to account for scaling effects due to the difficulty in attaining dynamical similarity in model testing (Harvald, 1983). These factors are the correlation allowance, the wake fraction, the thrust deduction fraction and the form factor. The propulsion factors were varied by amounts that were considered to represent the potential maximum uncertainty in the factor being studied. The propulsion factors that were varied are all values that are subject to the interpretation of the analyst and that can produce different results if the same model is tested and analysed at different facilities. The frictional resistance coefficient can be different depending on the choice of coefficient, e.g. ITTC 1957 or Grigson, as each line uses different formulas to determine the coefficient. Also, the model ship correlation line (ITTC 1957) and the turbulent flat plate friction line (Grigson and others) are based on empirical data and are subject to the uncertainty of the tests used to develop the lines. The correlation allowance is often based on a database of collected model data specific to the testing facility and can be subject to an uncertainty range (e.g. Manen & Oossanen, 1988, Resistance, 6.4 Table 13). The wake fractions and thrust deduction fractions are usually taken from the model data that represent the operating speed of the full-scale vessel; the values of w_{TS} and t in a model test series can vary by more than 10% over the test speed range (Table 3-20 and Table 3-22) (Bose *et al.*, 2005). It is difficult to measure ship resistance at low speeds and this can make it difficult to determine the form factor using Prohaska's method (Harvald, 1983).

Table 3-13 Original value of coefficient of friction and propulsion factors for ship subset

Ship	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ship #1	0.196	0.326	0.266	0.003047	0.001638	0.10
Ship #9	0.187	0.105	0.144	0.002769	0.001470	0.10
Ship #12	0.143	0.075	0.146	0.002933	0.001546	0.10
Ship #16	0.185	0.154	0.167	0.002680	0.001437	0.10
Ship #17	0.229	0.532	0.374	0.003135	0.001499	0.2791
Ship #21	0.327	0.063	0.185	0.003116	0.001674	0.40

The original values of the coefficient of friction and the propulsion factors as they are calculated within the method before they are varied are given in Table 3-13 for the 6 ships in the subset used for the detailed analysis. The correlation allowance is not calculated within the method but determined as an input factor, in this case the correlation allowance was assumed as 0.0004 for all the ships in the subset.

3.3.1 Variation of the frictional resistance coefficient

The frictional resistance coefficient was calculated within the ITTC 1978 method using the ITTC 1957 line, $C_{F1957} = \dfrac{0.075}{(\log_{10} Rn - 2)^2}$ (Harvald, 1983). The standard deviation that was applied to the frictional resistance coefficient was 0.0001 for the model and 0.00005 for the ship. These values of the standard deviations were determined by looking at the frictional resistance coefficient value when using different methods, in this case ITTC 1957, Grigson (1993) and Prandtl-Schlichting (Harvald, 1983). When looking at the subset of ship, the difference between the $C_{F\ 1957}$ and $C_{F\ \mathrm{Grigson}}$ for the model ranged from 0.00001-0.0001 and the difference between $C_{F\ 1957}$ and $C_{F\ \mathrm{Prandtl\text{-}Schlichting}}$ for the model was 0.00001, Table 3-14.

The standard deviation was assumed to be 0.0001 for the model for all data sets. The difference between the $C_{F\ 1957}$ and $C_{F\ \mathrm{Grigson}}$ for the ship was 0.0001 and the difference between $C_{F\ 1957}$ and $C_{F\ \mathrm{Prandtl\text{-}Schlichting}}$ for the ship was 0.00004. The lines are lower in value at full scale so the standard deviation for the ship was assumed to be half of the standard deviation of the model standard deviation, ± 0.00005 and the percentage variation was closer to the model scale. 0.0001 is approximately 3.4% of the average value of the $C_{F\ 1957\ \mathrm{M}}$ for the subset of 6 ships and 0.00005 is approximately 3% of the average value of $C_{F\ 1957\ \mathrm{S}}$. With respect to this uncertainty analysis it does not matter which line is used to calculate the coefficient of friction, the purpose of assigning a standard deviation was to test the uncertainty inherent in the empirical equation, the difference in the calculated values from the different lines was taken as a guide.

Table 3-14 Frictional coefficient comparison for ship subset

Model Scale								
	Length *m*	**Vel.** *m/s*	**Reynolds Number**	$C_{F\,1957}$	$C_{F\,\mathrm{Grigson}}$	$C_{F\,\mathrm{Prandtl\text{-}Schlichting}}$	**Diff. between** $C_{F\,1957}$ & $C_{F\,\mathrm{Grigson}}$	**Diff. between** $C_{F\,1957}$ & $C_{F\,\mathrm{Prandtl\text{-}Schlichting}}$
Ship #1	6.06	1.82	9.66E+06	0.00302	0.00296	0.00302	0.0001	0.00000
Ship #9	6.27	2.66	1.47E+07	0.00281	0.00280	0.00283	0.00001	-0.00002
Ship #12	5.42	2.31	1.10E+07	0.00295	0.00291	0.00296	0.00004	-0.00001
Ship #16	8.42	2.47	1.83E+07	0.00271	0.00273	0.00273	-0.00002	-0.00002
Ship #17	6.00	1.44	7.61E+06	0.00315	0.00305	0.00314	0.0001	0.00001
Ship #21	4.69	1.99	8.18E+06	0.00311	0.00302	0.00310	0.0001	0.00001
Ship Scale								
	Length *m*	**Vel.** *m/s*	**Reynolds Number**	$C_{F\,1957}$	$C_{F\,\mathrm{Grigson}}$	$C_{F\,\mathrm{Prandtl\text{-}Schlichting}}$	**Diff. between** $C_{F\,1957}$ & $C_{F\,\mathrm{Grigson}}$	**Diff. between** $C_{F\,1957}$ & $C_{F\,\mathrm{Prandtl\text{-}Schlichting}}$
Ship #1	124.4	8.2	6.17E+08	0.00163	0.00171	0.00167	-0.0001	-0.00004
Ship #9	158.0	13.4	3.20E+09	0.00133	0.00142	0.00136	-0.0001	-0.00003
Ship #12	130.0	11.3	8.86E+08	0.00155	0.00164	0.00159	-0.0001	-0.00004
Ship #16	210.5	12.3	1.57E+09	0.00145	0.00153	0.00149	-0.0001	-0.00004
Ship# 17	220.0	8.7	1.16E+09	0.00150	0.00159	0.00154	-0.0001	-0.00004
Ship #21	93.8	8.9	5.02E+08	0.00167	0.00176	0.00171	-0.0001	-0.00004

Also, Grigson (2000) has shown that when friction measurements of the drag on narrow pontoons were converted to drag coefficients and then compared to the Schoenherr line (Manen & Oossanen, 1988) the average curve through the measured points lay approximately 3% above the line.

The method of calculating the frictional resistance coefficient is automated within the program. The frictional resistance coefficient was varied by adding the standard deviation to the coefficient value after it was calculated ($\pm \sigma$).

When the frictional resistance coefficient (model & full-scale) was varied (Figure 3-20) the average standard deviation of the predicted powers in the subset was 6.58% over a range of 3.65% to 8.00%, (Table 3-16). The shortest ship with the shortest model, ship #21, (Table 3-14), had the smallest predicted power standard deviation. Ship #21 was over 30% shorter than the next longer ship and the predicted power standard deviation was 40% less than the next higher value. This indicates that although standard deviations of the model and ship frictional coefficients were all close in value, the lengths of the model and ship and the speed of the testing can influence the uncertainty of the predicted power of the full-scale vessel.

Table 3-15 Standard Deviation of frictional coefficient

	$C_{F\,1957}$ **Model**	**% standard dev**	$C_{F\,1957}$ **Ship**	**% standard dev**
Ship #1	0.00302	3.31%	0.00155	3.22%
Ship #12	0.00295	3.39%	0.00150	3.33%
Ship #16	0.00271	3.69%	0.00133	3.75%
Ship #21	0.00311	3.22%	0.00163	3.07%
Ship #9	0.00281	3.56%	0.00145	3.45%
Ship#17	0.00315	3.18%	0.00167	2.99%

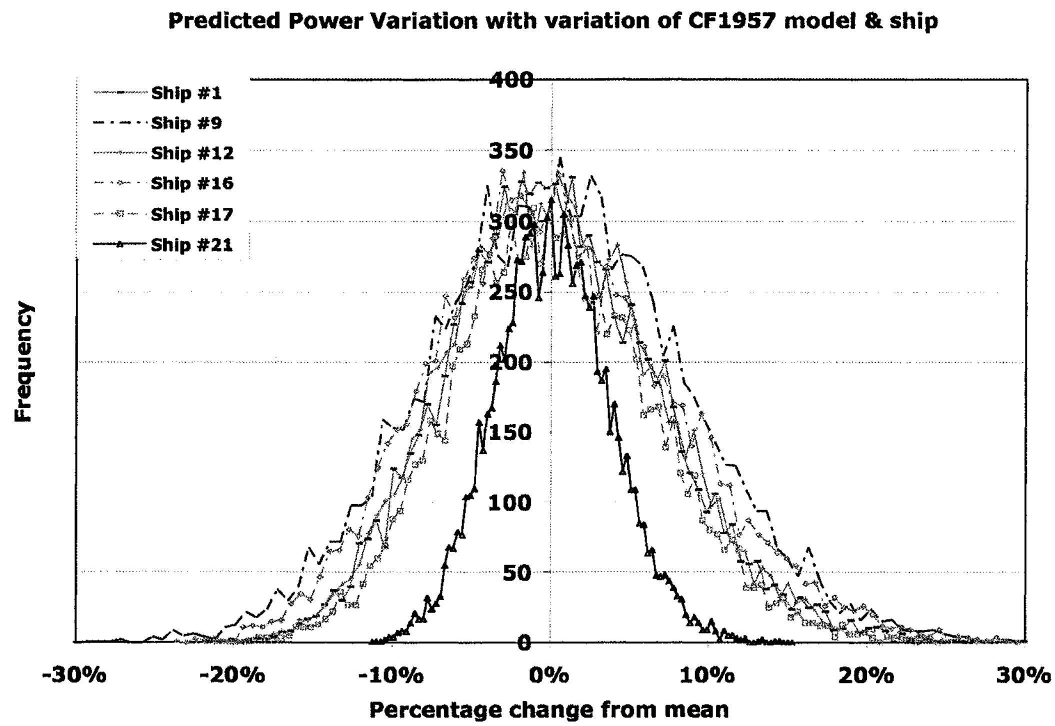

Figure 3-20 Comparison of predicted power variation when $C_{F\,1957}$ is varied

The standard deviation was the same magnitude for each ship studied and the percentage of the frictional coefficient varied from 3.18%-3.69% model scale and 2.99%-3.75% ship scale over the subset of ships, (Table 3-15).

This average standard deviation of predicted power is almost three times the standard deviation that resulted when just the measured inputs from the tests were varied because the assumed uncertainties of the frictional coefficients are high. If a 95% confidence were applied then the uncertainty of the predicted power would be ±12.89%.

Table 3-16 Comparison of standard deviations of full-scale values due to variation in $C_{F\ 1957}$

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ship #1	0.00%	0.67%	6.77%	1.33%	6.16%	0.00%	3.47%
Ship #9	0.00%	1.96%	8.00%	4.36%	6.06%	6.06%	6.87%
Ship #12	0.00%	0.69%	6.81%	2.89%	6.31%	6.31%	3.56%
Ship #16	0.00%	1.33%	7.87%	2.58%	6.54%	6.54%	3.46%
Ship #17	0.00%	1.33%	6.37%	3.12%	5.03%	0.00%	2.51%
Ship #21	0.00%	0.92%	3.65%	1.62%	2.76%	2.76%	1.63%
Average	**0.00%**	**1.15%**	**6.58%**	**2.65%**	**5.48%**	**5.42%**	**3.58%**

3.3.2 Variation of correlation allowance

As previously discussed, the correlation allowance, C_A, is a value that is added to the calculated smooth ship resistance coefficient to account for scale effects and other unknowns not considered by the other propulsion factors used in the ITTC 1978 extrapolation method. It is intended to correct for any difference between the model and full-scale values. Although the ITTC 1978 method includes an equation used to determine the correlation allowance, in practice it is thought to be different for different tanks (Manen & Oossanen, 1988, pg.61). When model test powering predictions are validated with full-scale trials, the difference between the model and full-scale values is corrected using the correlation allowance. A database of correlation allowances can then be built by a facility that corresponds to ship and propulsion system particulars. The correlation allowances specific to a testing facility are often examined and updated, based on experience.

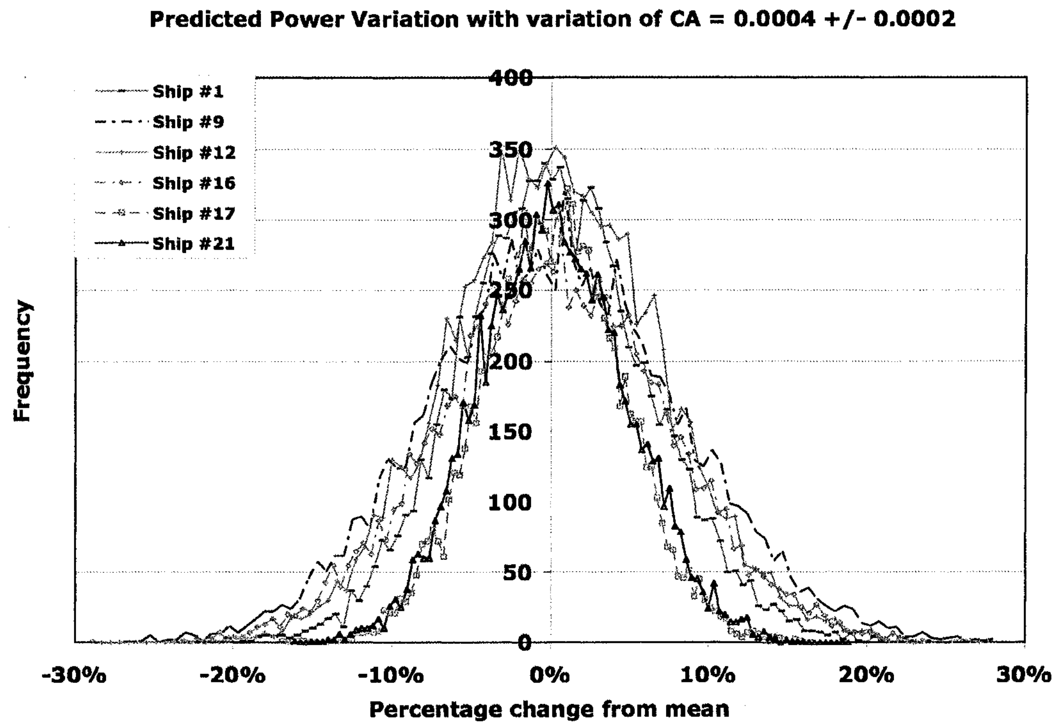

Figure 3-21 Comparison of predicted power variation when C_A was varied

At MARIN, Keller (1973, Manen & Oossanen, 1988, Resistance-Table 13) recommended values of correlation allowance to correspond to ship lengths; the range of these correlation allowances was from -0.00025 to +0.0004. Using the work of Keller and the correlation allowances published with some of the data included in the ITTC 2005 Ship Database (Bose *et al.*, 2005, Spencer *et al.*, 1990) the value for this analysis was assumed to be 0.0004 and C_A was assigned a standard deviation of 0.0002. Some facilities have worked with correlation allowances of up to 0.0006 (Bose *et al.*, 2005) and higher (Spencer *et al.*, 1992).

Because of the range of the correlation allowances in use and the fact that the term is used as a final catchall term in the correction for scaling effects, a standard deviation of

50% was chosen to allow investigation of the effect of the potentially large unknowns in correlation allowance.

The magnitude of the correlation allowance was assumed as a constant value and then input directly to the program.

The predicted power standard deviation was relatively consistent across the subset, (Figure 3-21). The average standard deviation of the predicted power was 5.67%, which translated to a 95% confidence uncertainty of approximately ±11.11%, again a high value.

Table 3-17 Comparison of standard deviations of full-scale values due to variation in C_A

Ship #1	0.00%	0.91%	5.94%	1.35%	5.02%	0.00%	5.54%
Ship #9	0.00%	1.96%	8.00%	4.36%	6.06%	6.06%	6.87%
Ship #12	0.00%	1.44%	6.66%	3.50%	5.22%	5.22%	5.66%
Ship #16	0.00%	1.70%	7.17%	3.35%	5.49%	5.49%	6.22%
Ship #17	0.00%	0.83%	4.40%	4.10%	3.57%	0.00%	4.14%
Ship #21	0.00%	1.67%	4.65%	3.44%	2.98%	2.98%	2.78%
Average	**0.00%**	**1.32%**	**5.67%**	**3.22%**	**4.36%**	**4.94%**	**4.81%**

3.3.3 Variation of form factor

The form factor is used in the ITTC 1978 method of extrapolation of powering data, however in the study by Bose *et al.*, (2005) only one of the eight institutions surveyed used Prohaska's method of form factor determination. One institute used an unspecified empirical formula and the remaining institutes set the form factor to zero for powering prediction. Testing is difficult at low Froude numbers (Harvald, 1983) and the magnitude of the form factor is affected by the quality of the data at low Froude numbers. Also, the form factor is subject to arbitrary variation during analysis, e.g. if a data point is observed to skew the analysis an analyst can choose to remove a point from the data set; different analysts can make different decisions.

The behaviour of the data can be misrepresented if the process is automated and for this reason the form factor was input as a set value to the program and then randomised. The intention here was to determine the potential effect of changing the estimated value of the form factor of a data set and not specifically to represent the best fit form factor for the ship model being tested.

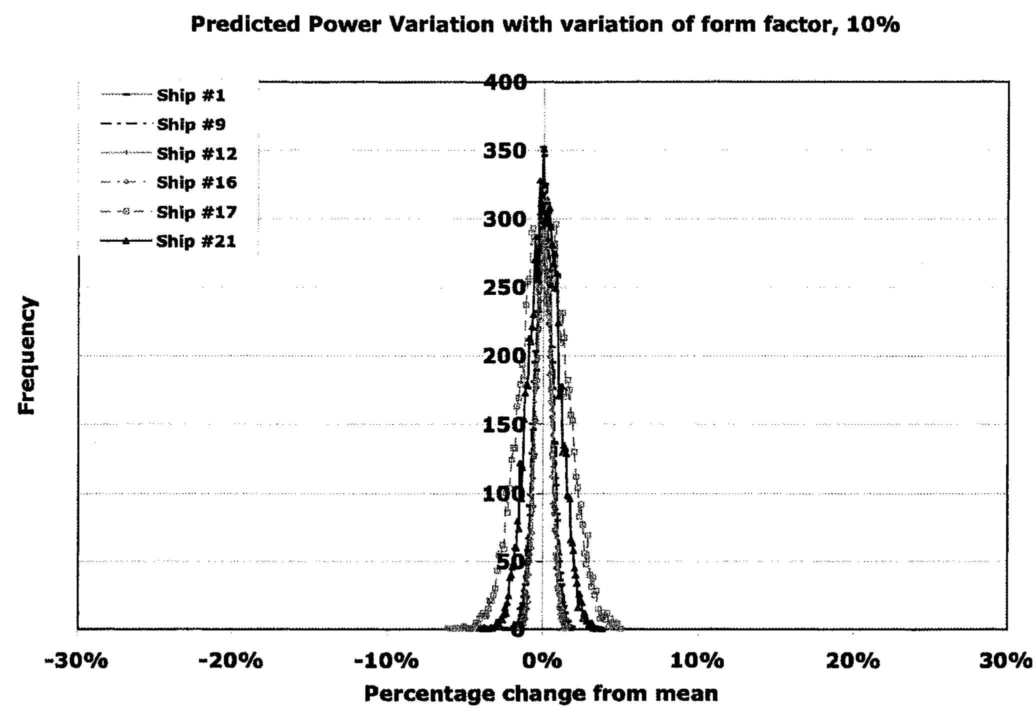

Figure 3-22 Comparison of predicted power variation when *k* was varied by 10%

Table 3-18 Comparison of standard deviations of full-scale values due to variation in k by 10%

Ship	V_S (m/s)	N_S (rps)	P_{DS} (kW)	T_S (N)	Q_{Sm} (Nm)	Q_S (Nm)	P_S (kW)
Ship #1	0.00%	0.11%	0.54%	0.23%	0.43%	0.00%	0.46%
Ship #9	0.00%	0.12%	0.56%	0.31%	0.45%	0.45%	0.54%
Ship #12	0.00%	0.09%	0.51%	0.27%	0.42%	0.42%	0.46%
Ship #16	0.00%	0.10%	0.45%	0.20%	0.35%	0.35%	0.40%
Ship #17	0.00%	0.42%	1.50%	0.31%	1.08%	0.00%	1.15%
Ship #21	0.00%	0.24%	1.01%	0.44%	0.77%	0.77%	0.92%
Average	**0.00%**	**0.18%**	**0.76%**	**0.29%**	**0.58%**	**0.49%**	**0.65%**

Two approaches were used in evaluating the effect of varying the form factor within the ITTC 1978 method. The first approach represented the potential uncertainty in the method of form factor determination and was assumed to be 10%.

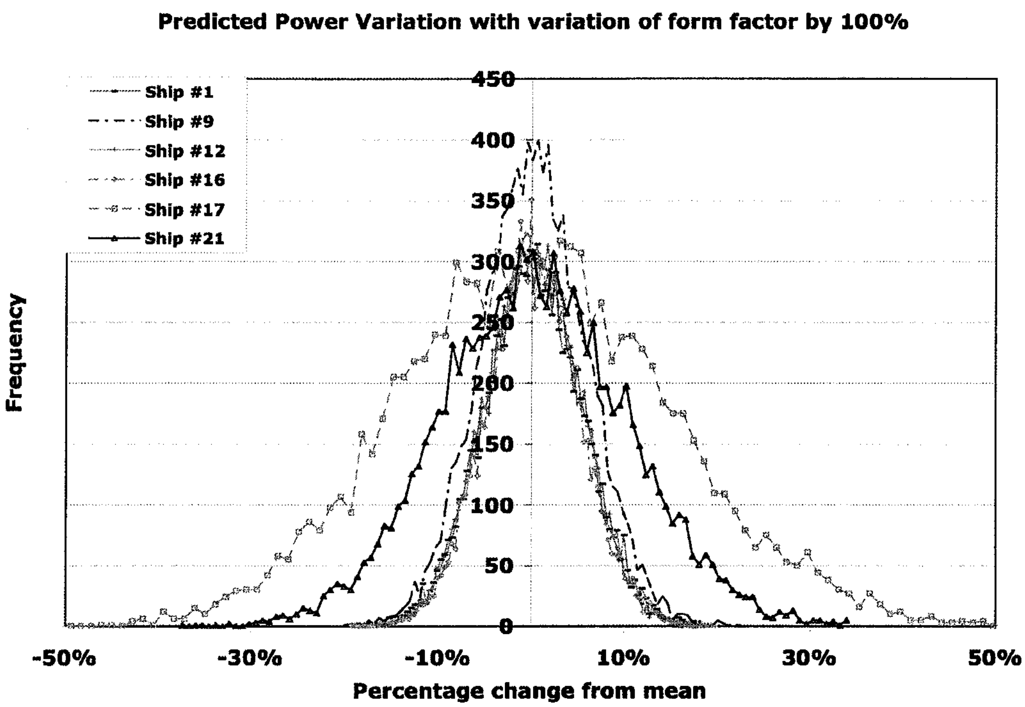

Figure 3-23 Comparison of predicted power variation when k was varied by 100%

The second approach represented the potential uncertainty in the choice of using a form factor versus not using a form factor; to show this a 100% standard deviation was used. The first standard deviation, (Figure 3-22), resulted in standard deviation of 0.76%, (Table 3-17), a low value that initially implies a minor affect on the results due to variation in form factor.

However, when the form factor was varied by 100%, Figure 3-23, the average standard deviation of the predicted power was 7.63%, much larger and in fact 10 times the size of the standard deviation that resulted when the form factor was varied at 10%. It is clear from these results that the choice to use or not use a form factor is significant and could potentially result in very different powering predictions for the same ship analysed at different facilities.

Table 3-19 Comparison of standard deviations of full-scale values due to variation in *k* by 100%

Ship #1	0.00%	1.11%	5.30%	2.30%	4.19%	0.00%	4.51%
Ship #9	0.00%	1.15%	5.66%	3.09%	4.50%	4.50%	5.39%
Ship #12	0.00%	0.94%	5.12%	2.76%	4.18%	4.18%	4.64%
Ship #16	0.00%	1.07%	4.97%	2.39%	3.90%	3.90%	4.52%
Ship #17	0.00%	4.15%	14.76%	3.15%	10.69%	0.00%	11.36%
Ship #21	0.00%	2.41%	9.99%	4.39%	7.61%	7.61%	9.14%
Average	**0.00%**	**1.81%**	**7.63%**	**3.01%**	**5.85%**	**5.05%**	**6.59%**

The predicted power standard deviations for ships #17 and #21 are much larger than predicted power standard deviations of the other ships in the subset. It must be noted that the form factor for ship #17 was almost 3 times the value of the form factor applied to the other model data (k=0.1) and for ship #21 the form factor was 4 times the value of the form factors applied to the other model data. This accounts for the higher standard deviations in predicted power and was demonstrated using ship #9; when a form factor of 0.2 was varied by a standard deviation of 100% the corresponding standard deviation of the predicted power was 11.75%.

3.3.4 Variation of wake fraction

The wake fraction is calculated for each speed tested and the speed that is extrapolated usually corresponds to the full-scale operating speed of the vessel

Table 3-20 Wake Variation with Speed

Ship #16			Ship #9			Ship #1	
V_M	w_M		V_M	w_M		V_M	w_M
[m/s]			[m/s]			[m/s]	
1.955	0.158		2.356	0.098		1.362	0.363
2.058	0.154		2.408	0.101		1.419	0.352
2.160	0.150		2.459	0.102		1.476	0.350
2.263	0.148		2.510	0.100		1.532	0.346
2.366	0.145		2.561	0.097		1.589	0.339
2.469	0.144		2.612	0.092		1.646	0.335
			2.664	0.093		1.703	0.332
						1.759	0.328
						1.816	0.325
						1.873	0.331
Max % Diff	9.77%			11.32%			11.17%
Standard Deviation	0.0052			0.0039			0.0121
% Deviation from mean	3.50%			4.03%			3.56%

The variation in the wake value can be large through the speed range and depending on how the analyst chooses to use the wake value the predicted power can be affected by this variation. Table 3-20 shows that in one test series the model wake can vary by at least 10% from the lowest to highest test speed.

In this study the model and ship scale wakes were varied separately by approximately 10%, (Table 3-13). The methods used to calculate the model and ship wakes in the ITTC 1978 method are outlined in Chapter 2. The model wake is a comparison of propeller open water and self-propulsion test advance ratios using the thrust identity method (Harvald, 1983) and the ship wake is calculated from the model wake, the thrust deduction fraction, the form factor and the frictional resistance coefficient. An additional value, 0.4, is included to accommodate the rudder effect (Manen and Oossanen, 1988); this is an empirical value based on tests completed prior to 1978 and as such may not be a relevant value for modern vessels. Also, the ITTC 1978 recommends that if the model wake is smaller than the ship wake then both values should be set equal to the model wake. Further work is needed on wake scaling.

The distribution of predicted power resulting from a 10% standard deviation in wake (model and ship) (Figure 3-24), had an uncertainty represented by an average standard deviation of 2.16% (Table 3-21).

There appear to be two ranges of data in Figure 3-24. Ships #1, #17 and #21 all have higher predicted power standard deviations than ships #9, #12 and #16 (Table 3-14). This is notable because the corresponding (respectively) model velocities are 1.82m/s, 1.44m/s and 1.99m/s for ships #1, #17 and #21, and 2.66m/s, 2.31m/s and 2.47 m/s for ships #9, #12 and #16, (Table 3-13). This implies that with slower model speeds the potential uncertainty in the predicted power with respect to uncertainty in both model and ship wake may be increased.

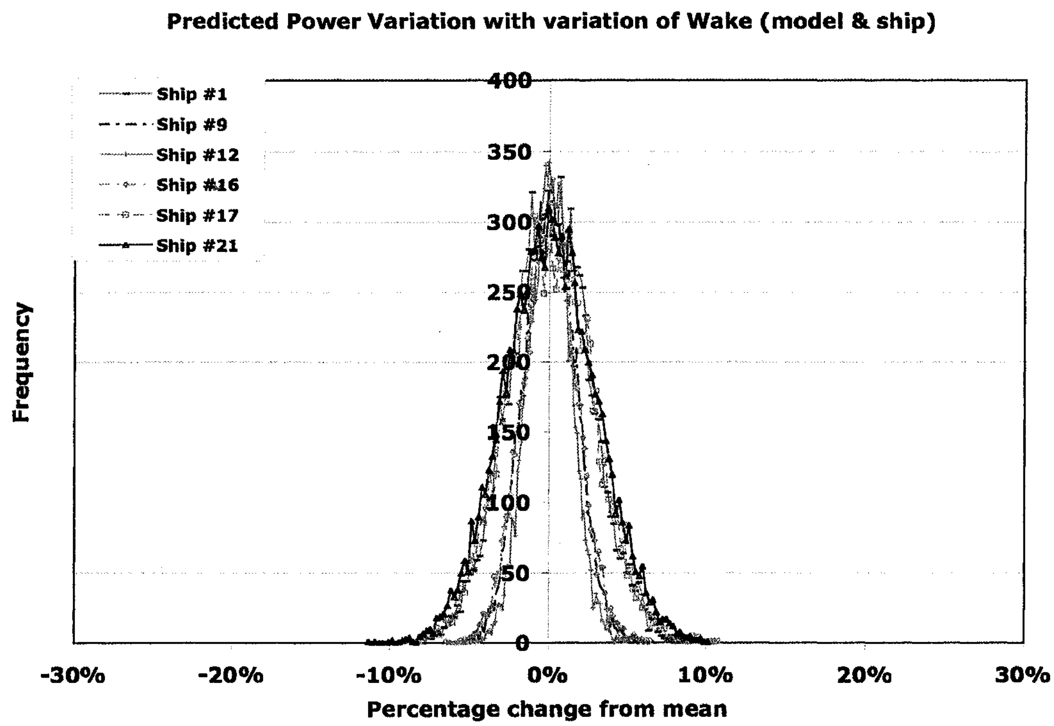

Figure 3-24 Comparison of predicted power variation when w_{TM} & w_{TS} were varied

Overall the magnitude of the uncertainty in the predicted power, 1 to 3% standard deviation, is not high and the method can be considered relatively stable with respect to uncertainty in the wake or wake scaling when studied alone. However in combination with other uncertainties from factors such as form factor and frictional coefficient the method shows less stability. This will be demonstrated in succeeding sections.

Table 3-21 Comparison of standard deviations of full-scale values due to variation in w_{TM} & w_{TS}

[illegible]							
Ship #1	0.00%	2.00%	2.58%	4.01%	0.58%	0.00%	0.00%
Ship #9	0.00%	1.03%	1.62%	1.61%	0.59%	0.59%	0.00%
Ship #12	0.00%	1.03%	1.38%	1.47%	0.34%	0.34%	0.00%
Ship #16	0.00%	1.13%	1.71%	2.30%	0.58%	0.58%	0.00%
Ship #17	0.00%	1.85%	2.70%	10.53%	0.85%	0.00%	0.00%
Ship #21	0.00%	1.73%	2.96%	4.12%	1.23%	1.23%	0.00%
Average	**0.00%**	**1.43%**	**2.16%**	**3.43%**	**0.70%**	**0.63%**	**0.00%**

3.3.5 Variation of thrust deduction fraction

The thrust deduction fraction for each model speed was calculated using the method described in Chapter 2 and Manen and Oossanen (1988). In the ITTC 1978 powering prediction procedure the thrust deduction value that is calculated for the model speed that corresponds to the full-scale operating speed of the vessel is used in the extrapolation of that speed.

The thrust deduction fraction can vary over 10% from the first to last speed tested (Table 3-23). For the analysis, each data set was varied by approximately 10% of the value calculated within the method when there was no randomisation. The thrust deduction fraction variation for ship #9 in Table 3-22 is very small; this is attributed to testing over a small range of velocities resulting in a small range of tow force, resistance and propeller thrust.

Table 3-22 Thrust deduction fraction variation with model test speed

Ship #16		Ship #9		Ship #1		Ship #12	
V_m	t	V_m	t	V_m	t	V_m	t
[m/s]		[m/s]		[m/s]		[m/s]	
1.955	0.189	2.356	0.188	1.362	0.169	1.955	0.189
2.058	0.185	2.408	0.187	1.419	0.194	2.058	0.185
2.160	0.178	2.459	0.187	1.476	0.210	2.160	0.178
2.263	0.171	2.510	0.188	1.532	0.218	2.263	0.171
2.366	0.174	2.561	0.187	1.589	0.221	2.366	0.174
2.469	0.184	2.612	0.187	1.646	0.216	2.469	0.184
		2.664	0.187	1.703	0.206		
				1.759	0.199		
				1.816	0.197		
				1.873	0.202		
Max Diff	10.43%		0.54%		13.93%		10.43%
Standard Deviation	0.0069		0.0004		0.0151		0.0069
% Deviation from mean	3.84%		0.22%		7.45%		3.84%

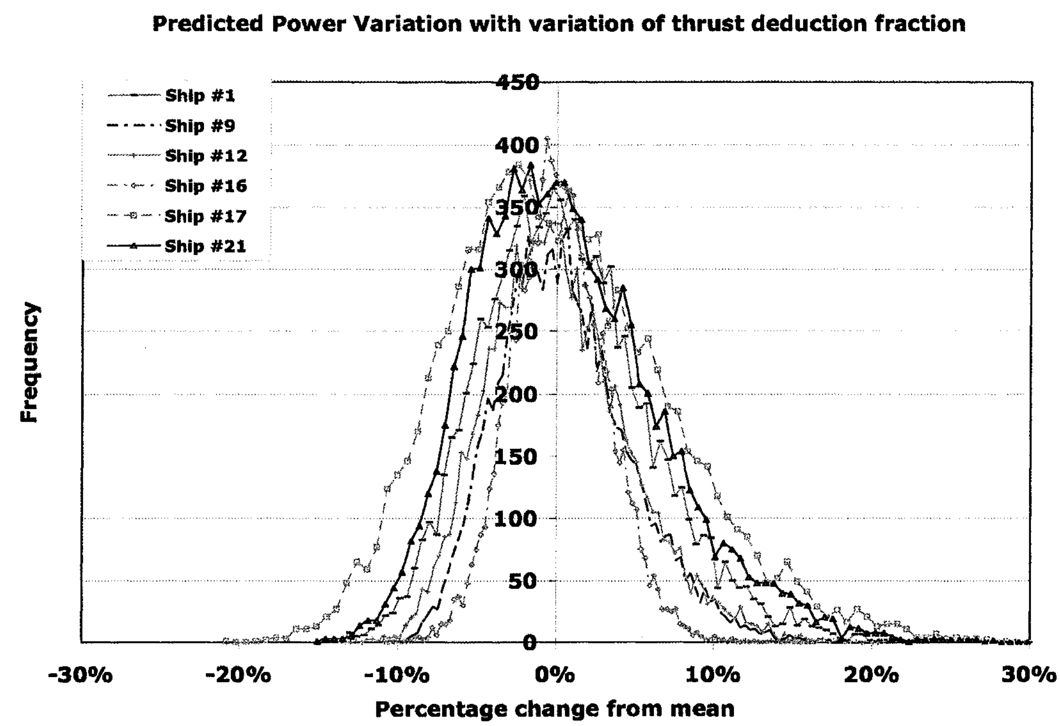

Figure 3-25 Comparison of predicted power variation when *t* was varied

The average standard deviation of the predicted power was 3.66% when the thrust deduction fraction was varied alone, (Table 3-23). There is a potential for a significant impact on the uncertainty of the predicted power due to standard deviation in the thrust deduction fraction. When a 95% confidence is applied, the uncertainty in predicted power ranges from 3.2% to 6.7%.

There is a skew in the predicted power distribution, because of the dependence of the thrust deduction fraction on the resistance. This skew is attributed to the resistance regression curves used in the extraplation (see section 3.2.3).

Table 3-23 Comparison of standard deviations of full-scale values due to variation in *t*

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ship #1	0.00%	0.02%	2.11%	0.03%	2.12%	0.00%	0.00%
Ship #9	0.00%	0.08%	1.65%	0.42%	1.72%	1.72%	0.00%
Ship #12	0.00%	0.14%	1.76%	0.47%	1.90%	1.90%	0.00%
Ship #16	0.00%	0.04%	1.75%	0.15%	1.72%	1.72%	0.00%
Ship #17	0.00%	0.53%	2.79%	1.81%	2.26%	0.00%	0.00%
Ship #21	0.00%	0.37%	3.45%	0.32%	3.08%	3.08%	0.00%
Average	**0.00%**	**0.20%**	**2.25%**	**0.53%**	**2.13%**	**1.40%**	**0.00%**

3.3.6 Variation of the frictional coefficient and all the propulsion factors together

The coefficient of friction and the propulsion factors were next varied together. The standard deviations of all the factors are those used in the individual analysis.

- $C_{F\,1957}$ – 0.0001 model & 0.00005 ship
- C_A – 0.0004 ± 0.0002
- k – 10% & 100%

- w_{TM} & w_{TS} – 10%
- t – 10%

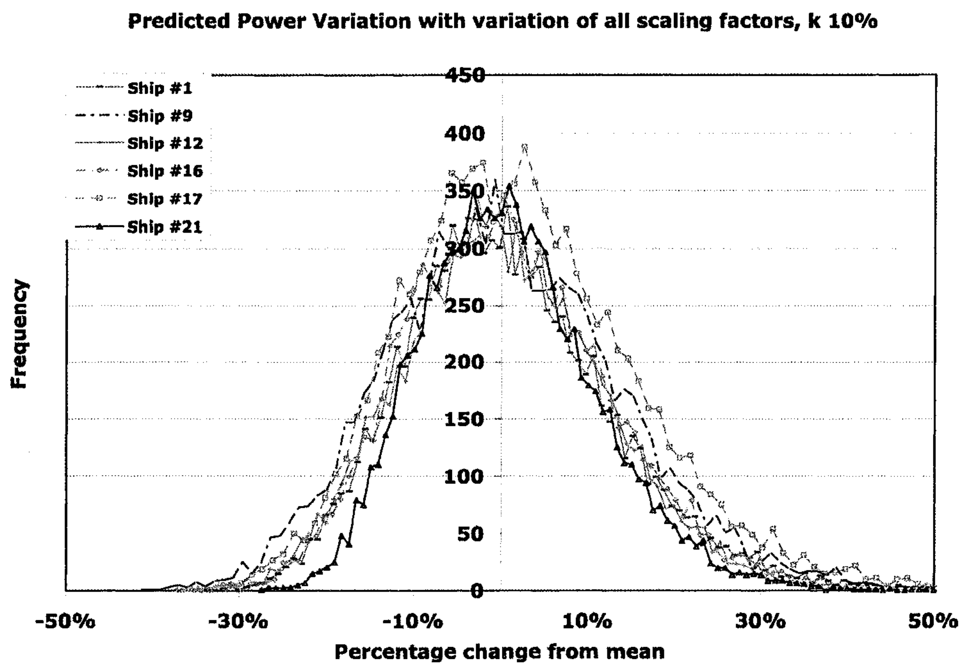

Figure 3-26 Comparison of predicted power variation when all the propulsion factors and the coefficient of friction (10%) were varied together

The average standard deviation of the predicted power when all the propulsion factors and the coefficient of friction are varied together is 10.84% (Table 3-24). The form factor in this case is varied by 10%.

If a form factor standard deviation of 100% is used then the average predicted power standard deviation is over 3% higher, 13.72%, Table 3-25. This clearly shows that the choice of whether or not to use a form factor has a highly significant impact on the uncertainty in the predicted power.

Table 3-24 Comparison of standard deviations of full-scale values due to variation in all the propulsion factors and coefficient of friction together, form factor 10%

Ship	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ship #1	0.00%	2.53%	10.61%	5.16%	8.87%	0.00%	6.86%
Ship #9	0.00%	3.12%	12.69%	6.87%	10.05%	10.05%	8.21%
Ship #12	0.00%	2.66%	10.84%	5.85%	8.93%	8.93%	6.91%
Ship #16	0.00%	2.97%	11.91%	5.95%	9.32%	9.32%	7.52%
Ship #17	0.00%	2.63%	10.52%	9.10%	8.04%	0.00%	5.69%
Ship #21	0.00%	2.71%	8.49%	5.56%	6.09%	6.09%	3.91%
Average	**0.00%**	**2.77%**	**10.84%**	**6.42%**	**8.55%**	**5.73%**	**6.52%**

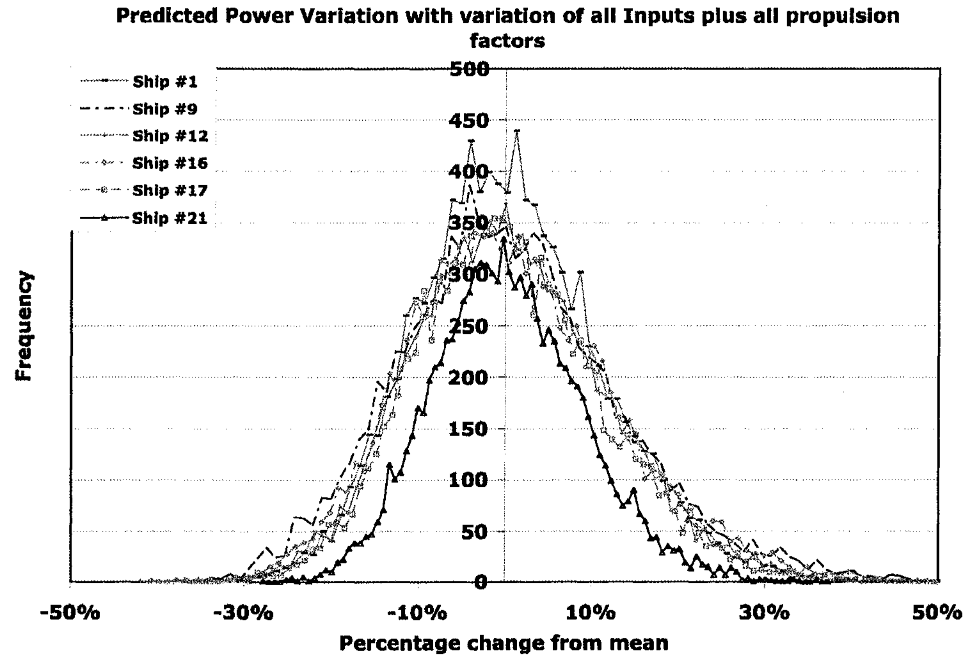

Figure 3-27 Comparison of predicted power variation when all the propulsion factors and the coefficient of friction (form factor was 10%) and measured test values were varied together

When the uncertainties of the measured test values were included with the variation of all the propulsion factors and the coefficient of friction by the previously discussed standard deviation values (the form factor standard deviation was 10%), there was little change in the average predicted power standard deviation.

Table 3-25 Comparison of standard deviations of full-scale values due to variation in all the propulsion factors and the coefficient of friction together, form factor 100%

Ship #1	0.00%	2.72%	11.50%	5.51%	9.54%	0.00%	7.89%
Ship #9	0.00%	3.33%	13.83%	7.50%	10.96%	10.96%	9.66%
Ship #12	0.00%	2.80%	11.74%	6.31%	9.65%	9.65%	8.01%
Ship #16	0.00%	3.11%	12.53%	6.25%	9.81%	9.81%	8.48%
Ship #17	0.00%	4.47%	16.74%	9.42%	12.57%	0.00%	11.87%
Ship #21	0.00%	4.56%	16.01%	8.50%	10.13%	10.13%	9.56%
Average	**0.00%**	**3.50%**	**13.72%**	**7.25%**	**10.44%**	**6.76%**	**9.24%**

The measured test values (e.g. thrust and torque of the propeller) were used to calculate the frictional resistance coefficient, the wake fractions and the thrust deduction fraction. Each of these values was applied a standard deviation directly and so the added effect of standard deviation in the measured test values on the predicted power was absorbed into the applied standard deviations. I.e. the value of the factor was calculated using the randomised measured value but then the factor was varied directly, essentially randomising a randomised number.

Table 3-26 Comparison of standard deviations of full-scale values due to variation in all the propulsion factors and the coefficient of friction and measured test values together, form factor 10%

Ship #1	1.00%	2.80%	10.85%	5.70%	9.06%	0.00%	8.33%
Ship #9	1.00%	3.31%	13.00%	7.05%	10.30%	10.30%	9.87%
Ship #12	1.00%	2.95%	11.23%	6.09%	9.19%	9.19%	8.78%
Ship #16	1.00%	3.20%	12.16%	6.32%	9.49%	9.49%	9.61%
Ship #17	1.01%	2.75%	10.79%	11.34%	8.29%	0.00%	7.15%
Ship #21	1.01%	2.88%	8.69%	5.87%	6.20%	6.20%	6.46%
Average	**1.00%**	**2.98%**	**11.12%**	**7.06%**	**8.75%**	**8.79%**	**8.37%**

A form factor standard deviation of 100% included in the standard deviation of propulsion factors, the coefficient of friction and the measured test values increased the average standard deviation of the predicted power to 13.76%.

To have 95% confidence in the predicted power when uncertainties of the levels used in this analysis (form factor standard deviation of 10%) (Table 3-26), are applied, the uncertainty of the results would be ± 21.25%, an unacceptable value in the analysis of ship data.

3.3.7 Variation of all propulsion factors and the coefficient of friction together including η_R

The previous sections evaluated the effect of test values, propulsion factors and the coefficient of friction on the predicted power when using the ITTC 1978 method. The relative rotative efficiency, η_R was set to 1 in the analysis to reduce the number of terms influencing the predicted power.

In order to show that overall the relative rotative efficiency has minimal impact on the standard deviation in predicted power, the analysis of section 3.3.6 was repeated with the relative rotative efficiency calculated automatically in the method.

The standard deviation in predicted power was on average 11.41%, (Table 3-27), versus 11.12% in section 3.3.6 (Table 3-26). The relative rotative efficiency has minimal impact on the uncertainty in the predicted power.

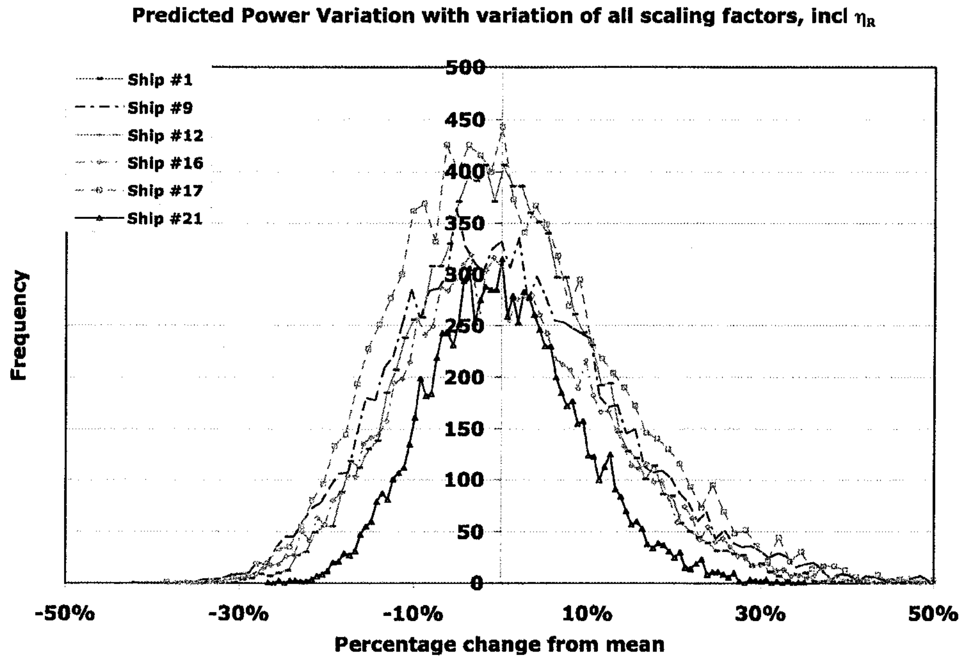

Figure 3-28 Comparison of predicted power variation when all the propulsion factors, the coefficient of friction (10%) and measured test values were varied together and the η_R was included

Table 3-27 Comparison of standard deviations of full-scale values due to variation in all the propulsion factors, the coefficient of friction and measured test values together, form factor 10% and including η_R

Ship	[illegible] (m/s)	[illegible]	P_{DS} (kW)	[illegible] (N)	Q_S [illegible] (Nm)	Q_S [illegible] (Nm)	[illegible] (kW)
Ship #1	1.00%	2.77%	10.72%	5.66%	8.95%	0.00%	8.41%
Ship #9	1.02%	3.33%	13.01%	7.10%	10.33%	10.33%	9.93%
Ship #12	1.00%	2.94%	11.00%	6.04%	9.09%	9.09%	8.58%
Ship #16	0.99%	3.20%	12.08%	6.31%	9.45%	9.45%	9.58%
Ship #17	1.01%	3.14%	12.96%	11.92%	9.95%	0.00%	7.13%
Ship #21	0.99%	2.88%	8.68%	5.79%	6.25%	6.25%	6.32%
Average	**1.00%**	**3.04%**	**11.41%**	**7.14%**	**9.01%**	**5.86%**	**8.33%**

3.4 Overall Comparison of Standard Deviations

The summary table, Table 3-28, shows that the factors that cause the highest standard deviations in predicted power are the frictional resistance coefficient, the correlation allowance and the form factor when varied by 100%.

Table 3-28 Overall Comparison of Standard Deviations

	$C_{F\,1957}$ Varied 3.4% (model) and 3% (ship)	Form Factor, *k*, Varied 10%	Form Factor, *k*, Varied 100%	Correlation Allowance Varied 50%	Wake, model & ship, Varied 10%
Ship #1	6.77%	0.54%	5.30%	5.94%	2.58%
Ship #9	8.00%	0.56%	5.66%	8.00%	1.62%
Ship #12	6.81%	0.51%	5.12%	6.66%	1.38%
Ship #16	7.87%	0.45%	4.97%	7.17%	1.71%
Ship #17	6.37%	1.50%	14.76%	4.40%	2.70%
Ship #21	3.65%	1.01%	9.99%	4.65%	2.96%
Average	**6.58%**	**0.76%**	**7.63%**	**6.14%**	**2.16%**

	Thrust deduction fraction varied 10%	$C_{F\,1957}$, *k*10%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, *k*10%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, *k*100%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied
Ship #1	2.11%	10.61%	10.85%	11.85%
Ship #9	1.65%	12.69%	13.00%	14.14%
Ship #12	1.76%	10.84%	11.23%	12.22%
Ship #16	1.75%	11.91%	12.16%	12.82%
Ship #17	2.79%	10.52%	10.79%	16.73%
Ship #21	3.45%	8.49%	8.69%	14.78%
Average	**2.25%**	**10.84%**	**11.12%**	**13.76%**

These values were varied by an amount considered to be representative of the maximum potential uncertainty in the frictional resistance coefficient, the correlation allowance and the form factor and they can be altered to more accurately represent the variations specific to a particular facility. The values that were chosen give a clear picture of the effect of the various components in the ITTC 1978 method on the powering predictions. The combined standard deviations of the measured test values (all inputs in Table 3-28), the coefficient of friction and propulsion factors resulted in a high level of uncertainty in the predicted power. For 95% confidence the uncertainty was ± 11.12%*1.96= ±21.80% when the standard deviation of the form factor was 10%. When the standard deviation of the form factors was 100% and combined with the uncertainty in the input values, the coefficient of friction and propulsion factors, then the uncertainty in the predicted power rose to ± 26.80%. These potential levels of uncertainty are unacceptable in the prediction of ship powering.

3.4.1 Summary

The prediction of ship powering using the ITTC 1978 method has been shown to be relatively sensitive due to uncertainty in the frictional coefficient, the correlation allowance and the form factor. When the frictional resistance coefficient is varied by a standard deviation 3.4% (model) and 3% (ship), there is a corresponding standard deviation in predicted power of over 6.5% and therefore within a 95% confidence limit the predicted powering result has an uncertainty of ± 12.9%. A 50% standard deviation in correlation allowance may initially appear high, however this represents the choice between for example, a correlation allowance of 0, 0.0002 and 0.0004. With this uncertainty in correlation allowance the corresponding standard deviation in power is 6.14%, ±12% if a 95% confidence is applied. The choice of using versus not using a form factor results in the potential for the power to be ± 15% of the predicted value when a 95% uncertainty is applied. When the uncertainty in these three factors is combined with representative uncertainties in the remaining factors and in the test results the average final power uncertainty with 95% confidence is over 21%. The standard deviations that were chosen for these factors may be considered high, however even half of the potential predicted uncertainty in power, ± 11-14% is of concern.

All the propulsion factors, the coefficient of friction and the measured values are used together to determine the ship propeller operating point of the method (see Chapter 2 and Manen and Oossanen 1988) and this has been determined to be a primary source of the instability in the ITTC 1978 method.

The interpolation equation, $\frac{K_{TS}}{J_O^2} = \frac{S_S C_{TS}}{2D_S^2(1-t)(1-w_{TS})^2}$, is used in combination with the ship propeller open water data to determine the ship propeller operating point and in turn the full scale operating parameters (shaft speed, delivered power, etc.). The ship scale resistance coefficient, $C_{TS} = (1+k)C_{FS} + C_{RS} + C_A + C_{AA}$, is directly dependent on the frictional resistance coefficient, the correlation allowance and the form factor. Also, the ship scale wake fraction, $w_{TS} = (t+0.04) + (w_{TM} - t - 0.04)\frac{C_{VS}}{C_{VM}}$, where $C_{VS} = (1+k)C_{FS} + C_A$ and $C_{VM} = (1+k)C_{FM}$, is dependent on the frictional resistance coefficient, the correlation allowance and the form factor. The factors that have been shown to produce the highest uncertainty in power when varied are all used directly in this equation.

Improvements to the method should be focused on modifying the way the frictional resistance coefficient, correlation allowance and form factor are used within the method and in particular in the interpolation of the ship propeller operating point.

Approaches that can be used to improve the ITTC 1978 powering prediction method are discussed in Chapter 6 and include the following:

- Use an alternate method of obtaining the ship propeller operating point.
- The reliability of the frictional resistance coefficient could be improved by choosing a turbulent flat plate friction line such as that by Katsui *et al.*, (2003) or Grigson, (2001) for example. These are modern friction lines that were obtained through numerical integration of local friction in the boundary layer and represent the frictional resistance of the model and ship. The ITTC 1957 correlation line, presented almost 50 years ago, was presented initially as an interim solution to the problem of scaling the frictional resistance and was not intended to represent the frictional resistance of a plane or curved surface (Manen and Oossanen, 1988, Grigson, 2000).
- Evaluate the importance of using three separate tests to determine the full-scale results. The additional uncertainty in synchronizing the data to one speed could be eliminated if one test was used instead.
- Assess the method used to determine the thrust deduction fraction. There is a potential for significant uncertainty in the ITTC 1978 method because to calculate the thrust deduction fraction only one resistance value is extrapolated and compared with one thrust

value. Using the results of a load varying self-propulsion test, the slopes of all of the tow force-thrust lines are used to determine the thrust deduction fraction (Chapter 2, Molloy 2001, Holtrop 2001) so the additional data points, as has been shown, will reduce the uncertainty of the thrust deduction fraction.

- Determine alternate approaches to wake scaling. For example, Holtrop (1982) has proposed an alternate wake formula based on a statistical analysis of model and ship trials data.
- Develop a new database of correlation allowances. Using regression the ITTC 2005 ship database (Bose *et al.*, 2005) could be used to develop a comprehensive set of correlation allowances that could be validated and customised for individual institutions.

Chapter 4

Variation in the E2001 Method

The E2001 extrapolation method described in Chapter 2 is a method that uses only self-propulsion tests to predict full scale powering from model tests. These tests are performed as load-varying tests and the load is varied to include thrust values over a large range. The method is described in part by Holtrop (2001) and by Molloy (2001).

The E2001 method differs from the ITTC 1978 method in the following ways:

- First the ITTC 1978 method uses three physical tests while the E2001 uses one.
- The E2001 method uses a value to represent the resistance of the model by forcing the thrust negative in load varying tests and assuming that the towing force at zero thrust, $F_{D@T=0}$, represents the resistance, (see section 2.1).
- The thrust deduction fraction is determined from the equation of the line created when the tow force is plotted linearly against the thrust; $F_D = T_M(t-1) + F_{D@T=0}$ where t is the thrust deduction fraction.

- The full-scale thrust is calculated from $T_S = \left\{ \frac{F_{T=0} - F_D}{1-t} \right\} \lambda^3 \frac{\rho_S}{\rho_M}$ where λ is the scale factor and ρ is the density (Iannone, 1997).
- This value of thrust is then used to calculate the remaining full-scale parameters through determination of the ship propeller operating point from the full-scale thrust and torque coefficients (Chapter 2 and Holtrop, 2001) and the interpolation equation $K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$ (Holtrop 2001, Molloy 2001).

The E2001 method uses the following coefficient of friction and propulsion factors in the extrapolation of power; the frictional resistance coefficient, C_F, the form factor, k, the correlation allowance, C_A, are used in the calculation of the tow force. The thrust deduction fraction, t, is used in the calculation of the full-scale thrust ($T_S = \left\{ \frac{F_{T=0} - F_D}{1-t} \right\} \lambda^3 \frac{\rho_S}{\rho_M}$). In lieu of a wake fraction, a wake scale effect (Holtrop, 2001), $w_{scale} = \frac{\left(V_A/V \right)_S}{\left(V_A/V \right)_M}$ (Holtrop 2001), is applied to the thrust and torque coefficients,

$$K_{TS} = a_1 \left(w_{scale} J \right)^2 + b_1 \left(w_{scale} J \right) + c_1 - \Delta K_T \quad \& \quad K_{QS} = a_2 \left(w_{scale} J \right)^2 + b_2 \left(w_{scale} J \right) + c_2 - \Delta K_Q$$

(Chapter 2 and Holtrop 2001), to correct for the comparatively higher thrust loading at model scale without using propeller open water tests. The thrust and torque coefficients are expressed as polynomials, determined from the model data using a least squares method, in order to straightforwardly apply the wake scaling directly to the propeller advance coefficient. The value used for the wake scale effect can be determined from a database of correlated model and ship trial data or from a semi-empirical formula such as that presented by Holtrop and Mennen (1982). Not unlike the correlation allowance used in practice at most institutions, the reliability of the wake scaling is dependent on the size and diversity of available data.

The E2001 method has been shown to predict power that is close in value to that predicted using the ITTC 1978 method and to the corresponding full-scale trials data (Molloy, 2001). Using the model test data and corresponding full-scale trials data of an RClass icebreaking vessel (a vessel that was studied in a research project that analysed model and full-scale performance and used the load varying test method for the model self-propulsion tests (Spencer *et al.*, 1992)) the E2001 prediction method results were compared to the ITTC 1978 powering prediction method results and the corrected full scale results. Aspects of the method were considered in detail, e.g. the wake scaling and thrust deduction fraction values calculated within each method were compared. The predicted results were also compared for different frictional resistance coefficient and different correlation allowances and all results were compared with full-scale values (Molloy, 2001).

The variation of the values input to the E2001 method was completed using the same Monte Carlo Simulation with 10,000 iterations and order of variations as the procedure used to analyse the ITTC 1978.

4.1 Variation of measured test inputs

The test inputs that were varied using the E2001 method were those obtained from a self-propulsion test only (Table 4-1). There are no resistance or open water test results required to extrapolate the power in the E2001 method. As in the ITTC 1978 analysis, each test value was varied by 1% of the maximum value. The E2001 method requires load-varying test data.

Table 4-1 Measured Value Inputs

Tests	Parameters varied	% Standard Deviation
Self-propulsion test	V_M, n_M, T_M, Q_M, F_D	1%

Load varying tests are tow tests where the load on the propeller is varied around the expected value of the self-propulsion point, a series of runs in the tow tank are completed and the shaft speed, n_M, is changed for each run producing a new tow force, thrust and torque loading each time. The self-propulsion point is interpolated using the ship self-propulsion point equation $F_D = \frac{1}{2}\rho_M V_M{}^2 S_M\left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$ used in the ITTC 1978 method (Manen & Oossanen, 1988). The purpose of this load-varying method is to reduce the uncertainty in obtaining the self-propulsion point; it has been shown that more reliable power predictions result from an interpolation of the self-propulsion point from a series of tests performed at values around the self-propulsion point, than tests run with parameters set at the self-propulsion point (Kracht, 1991).

In Chapter 3 the data sets used in the analysis all had non-load varying or Continental method self-propulsion test results. When studied, a standard deviation of 1% of the value of each of the self-propulsion point parameters (V_M, n_M, T_M, Q_M, F_D) was applied and so the self-propulsion point of each data set was varied by a standard deviation of 1%. When load-varied data was randomised, each of the self-propulsion point parameters was varied by a standard deviation of 1% of the maximum value in the test set for each run, which resulted in a slightly larger standard deviation of the self-propulsion point than 1% (see self-propulsion point description in Chapter 2). For example, in one test series with 7 test runs in the self-propulsion test, the values of total thrust ranged from 68N to 138N and each of the 7 values of the test series was varied by a standard deviation of 1.38N. The 1% of maximum value approach was maintained for consistency and although it may appear that there was a higher uncertainty in the overall powering results when load varied self-propulsion tests were used, this is because each model test maximum value (and therefore each 1% standard deviation) was larger in the load varied self-propulsion test input file than in the Continental method self-propulsion test input files. Additionally, Kracht (1991) found that the load varied self-propulsion test has less uncertainty in estimating the self-propulsion point than the non-load varied self-propulsion test.

There was only one set of load-varied tests in the database, the ship #21 data. In order to compare like with like, when the ITTC 1978 method analysis was completed (Chapter 3) the self-propulsion point of the load varied data was calculated and then input to the program as though it were non-load varied data. However the full set of load-varied data was used when analysing the data using the E2001 method.

All measured values varied together

First the measured values were varied together using the Monte Carlo simulation (10,000 iterations) and the results predicted using the E2001 method were compared to the predicted results for the subset of 6 ships that were analysed using the ITTC 1978 method, Figure 4-1.

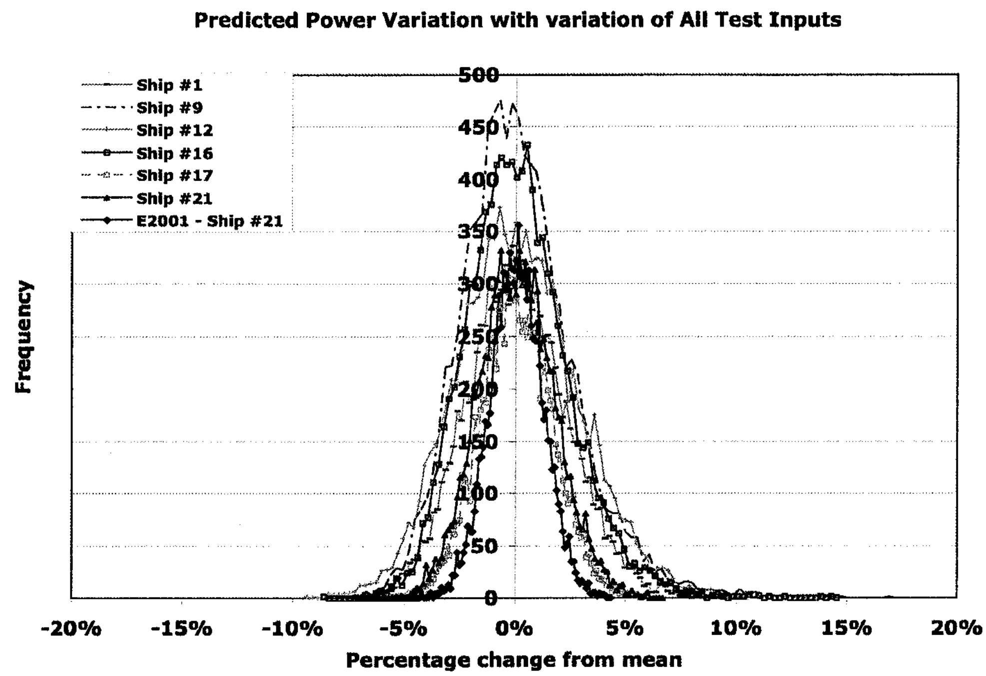

Figure 4-1 Comparison of predicted power variation when all measured test values are varied using ITTC 1978 and E2001

The predicted standard deviations of the full-scale powers, velocities, shaft speeds, thrusts and torques are compared in Table 4-2. The predicted standard deviation for each of the full-scale operating parameters was smaller when the E2001 method was used than when the ITTC 1978 method was used. The standard deviation of the predicted power using the E2001 method was 1.21% compared to an average of 2.22% for the 6-ship subset analysed with the ITTC 1978 method. Again, as with the previous plots of predicted power distributions, the varying height of the curves is due to the automatic binning process that was used for expediency, but graphical representation of the standard deviation was unaffected.

Table 4-2 Comparison of predicted standard deviations when measured input values varied

Ship #1	1.01%	1.42%	2.28%	3.04%	1.77%	0.00%	5.11%
Ship #9	0.99%	1.53%	2.60%	2.22%	1.71%	1.71%	5.54%
Ship #12	0.99%	1.66%	2.76%	2.23%	2.16%	2.16%	5.60%
Ship #16	1.00%	1.57%	2.35%	2.81%	1.49%	1.49%	6.16%
Ship #17	1.00%	0.67%	1.63%	7.56%	1.52%	0.00%	4.14%
Ship #21	0.99%	1.01%	1.72%	2.26%	0.91%	0.91%	4.91%
Average of 6 ship subset using ITTC 1978 method	***1.00%***	***1.31%***	***2.22%***	***3.35%***	***1.59%***	***1.05%***	***5.24%***
E2001 - Ship #21	1.00%	0.71%	1.21%	0.64%	0.98%	0.94%	2.61%

The standard deviations of the other full-scale parameters, ship velocity, V_S, ship shaft speed, n_S, ship thrust, T_S, ship torque, Q_S, effective power of the ship, P_{ES}, when predicted using a standard deviation of 1% on all measured values input to the E2001 method are smaller than the average standard deviation of the predicted values of the subset evaluated with a standard deviation of 1% in the measured values in using the ITTC 1978 method. The largest differences are between the predicted standard deviations of the thrust and the effective power, a difference of close to 3% for each.

This is of note because the treatment of the data within the program causes the variation of the actual self-propulsion point when using load varied test data to be slightly more than 1%.

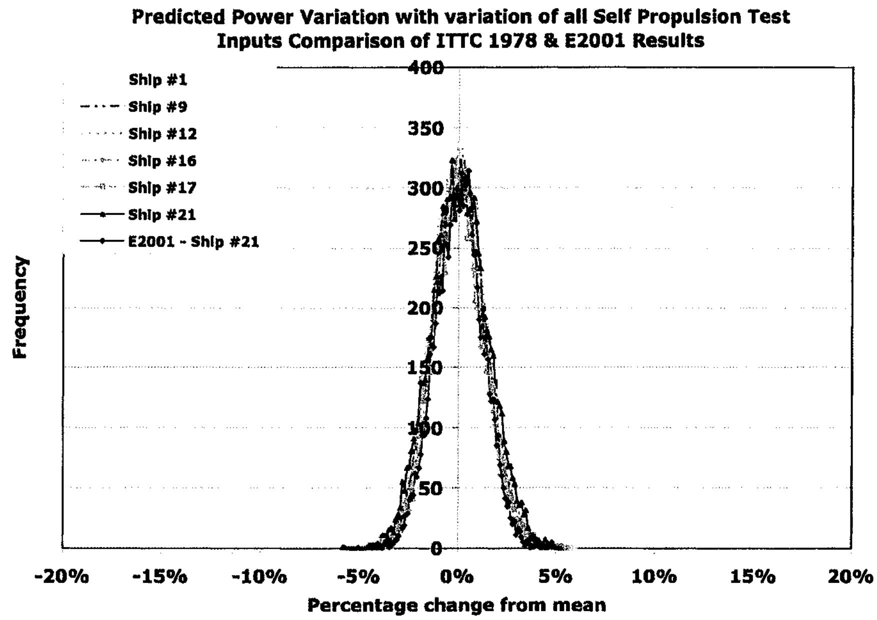

Figure 4-2 Comparison of predicted power distributions resulting when self-propulsion test values are varied

The effect of the uncertainty in the self-propulsion test data on the predicted full-scale values using the ITTC 1978 method was evaluated in Chapter 3.2.4. The predicted full-scale standard deviation results when all measured test values were varied by a standard deviation of 1% determined using the ITTC 1978 method were compared to the same results using the E2001 method. Only the results from variation in the self-propulsion test data were compared because only the data from the self-propulsion test were used in the extrapolation of power using the E2001 method. There was no comparison to open water or resistance data. The results in Table 4-3, *SP* column, show that using the E2001 method resulted in lower standard deviations in the predicted power than the ITTC 1978 method when the measured test values from the self-propulsion test alone were varied.

Table 4-3 Standard deviations of predicted power when inputs from self-propulsion test are varied individually

	***SP* All values together**	***V* alone**	***n* alone**	***F_D* alone**	***T* alone**	***Q* alone**
Ship #1	1.37%	0.93%	0.69%	0.33%	0.66%	1.00%
Ship #9	1.35%	0.92%	0.86%	0.36%	0.36%	0.36%
Ship #12	1.36%	1.12%	0.70%	0.35%	0.44%	1.00%
Ship #16	1.28%	0.88%	0.83%	0.41%	0.20%	0.99%
Ship #17	1.32%	0.49%	0.64%	0.66%	0.81%	1.00%
Ship #21	1.46%	1.02%	0.17%	0.17%	0.44%	1.00%
Average	***1.36%***	***0.89%***	***0.65%***	***0.38%***	***0.49%***	***0.89%***
E2001 – Ship #21	1.21%	0.46%	0.51%	0.25%	0.82%	0.48%

Each of the standard deviations of the power predicted using the E2001 method when each individual measured parameter from the self-propulsion test was varied alone (Figure 4-2 to Figure 4-7) was lower than the average power standard deviation obtained when the ITTC 1978 method was used with the exception of thrust; when thrust was varied alone the standard deviation of the predicted power using the E2001 method was approximately double the ITTC 1978 value (Table 4-3). This is because the model thrust was treated differently in the prediction of full-scale thrust and power in the E2001 method than in the ITTC 1978 method (see Chapter 2).

The standard deviation of the power predicted using the E2001 method when there was 1% standard deviation in self-propulsion test velocity was 0.46% versus a predicted power standard deviation of 0.76% when the power was predicted using the ITTC 1978 method (see Table 4-3). The value of standard deviation obtained using each of the methods was small; the standard deviation in power was less than the standard deviation in the input velocity indicating that with respect to the uncertainty in the velocity each method is stable.

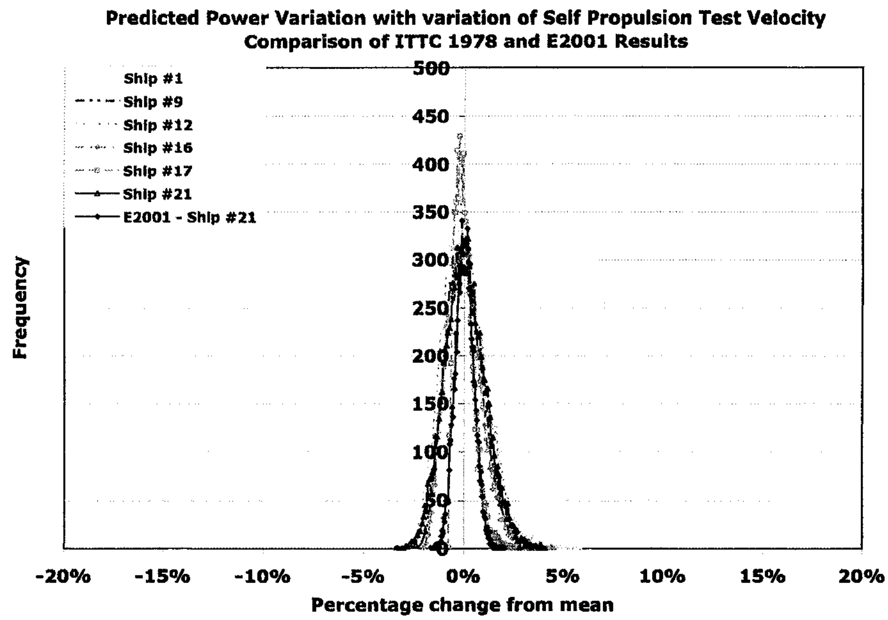

Figure 4-3 Comparison of predicted power distributions resulting when self-propulsion test velocity was varied

The standard deviation of the power when predicted with E2001 with a standard deviation of the shaft speed was also insignificant, and again the value obtained using the E2001 method, 0.51% was lower than the average value obtained when the power was predicted using the ITTC 1978 method, 0.65% (see Table 4-3).

The thrust resulted in a larger standard deviation in the predicted power than the other test values and than the value predicted using the ITTC 1978 method because the thrust from the self-propulsion test is used repeatedly through the E2001 prediction method, e.g. the tow force at zero thrust is calculated using the model thrust and tow force linear relationship, $F_D = T_M(t-1) + F_{D@T=0}$ and then the full-scale thrust is scaled directly, $T_S = \left\{\frac{F_{T=0} - F_D}{1-t}\right\}\lambda^3 \frac{\rho_S}{\rho_M}$, the shaft speed is determined using the full scale thrust and the thrust coefficient of the ship, $n_S = \sqrt{\left[\frac{T_S}{K_{TS} D_S^4 \rho_S}\right]}$.

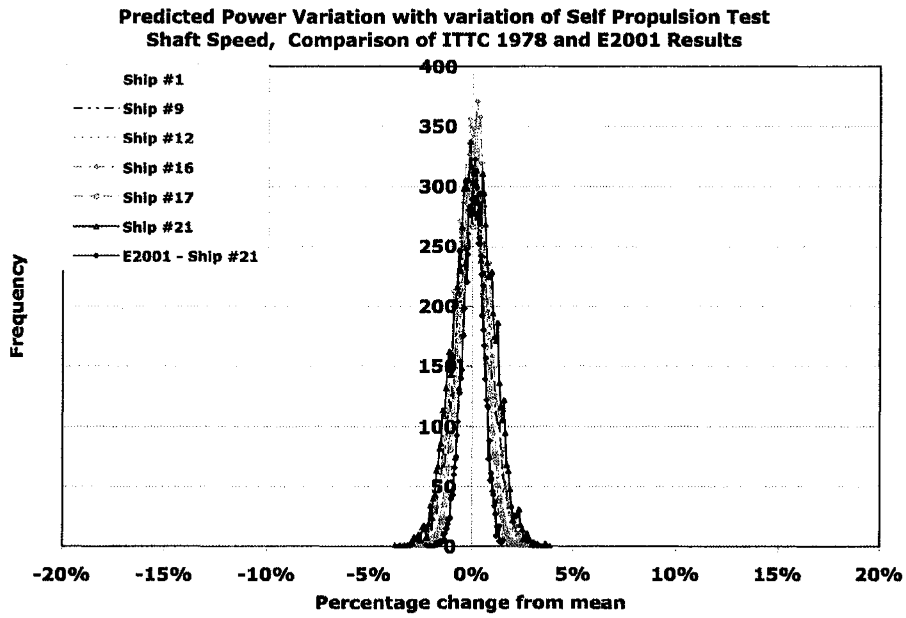

Figure 4-4 Comparison of predicted power distributions resulting when shaft speed was varied

In the ITTC 1978 method the thrust of the self-propulsion test is used first to determine the model propeller characteristics and then to determine the thrust deduction fraction, the propeller open water test results are used to interpolate the full-scale parameters (see Chapter 2 and Figure 4-5 and Table 4-3). This demonstrates that while the resulting uncertainty in power was not large, accurate thrust measurements in the self-propulsion test are an important consideration when extrapolating model data using the E2001 method.

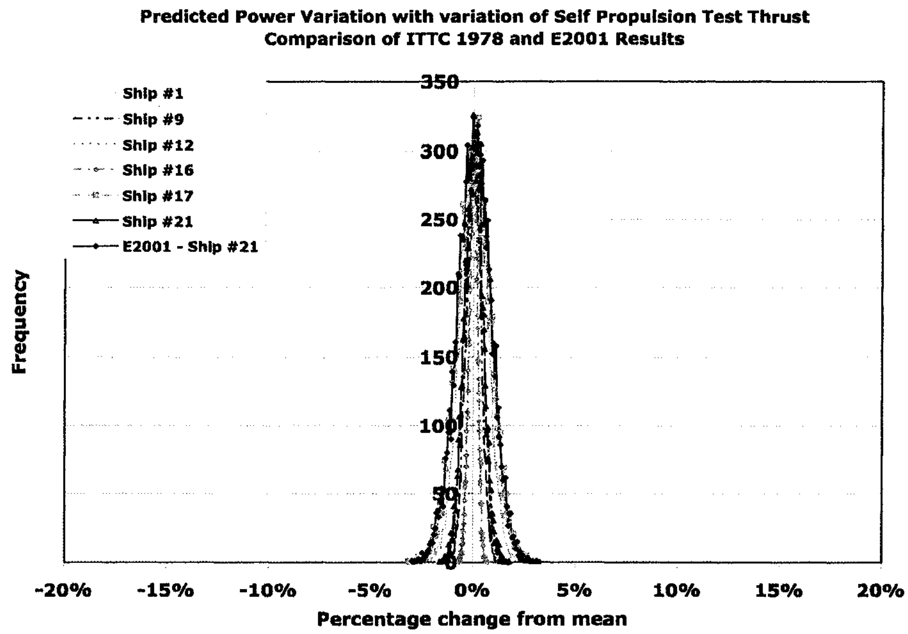

Figure 4-5 Comparison of predicted power distributions resulting when thrust was varied

When the power was predicted using the ITTC 1978 method and only the self-propulsion test torque was varied by a standard deviation of 1%, the standard deviation in predicted power was a direct result of the relative rotative efficiency η_R because the torque from the self-propulsion test is only used in determining the relative rotative efficiency and is otherwise not used in the ITTC 1978 method (see Chapter 2 and Manen & Oossanen, 1988). In the E2001 method the torque from the self-propulsion test is used throughout the method to predict the power and because open water test data is not used, there is no relative rotative efficiency used in the E2001 method. The standard deviation in predicted power was higher when the ITTC 1978 method was used and the torque was varied by a standard deviation of 1%, the average standard deviation was 0.89% and when the E2001 method was used (Figure 4-6) the standard deviation of the predicted power was 0.46%.

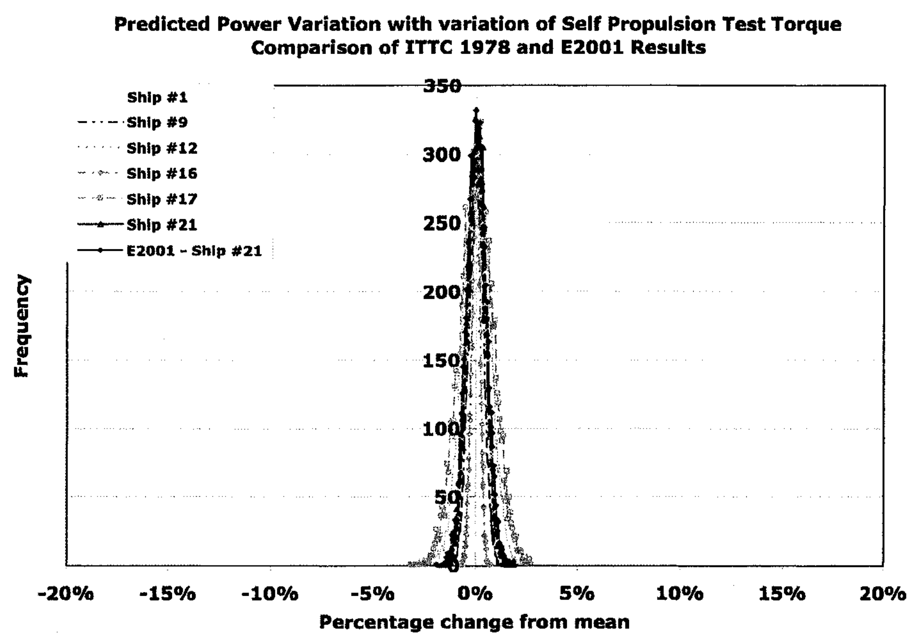

Figure 4-6 Comparison of predicted power distributions resulting when torque was varied

The effect of standard deviation in the tow force on the uncertainty in predicted power was relatively insignificant (< 0.4% standard deviation in power) when either method was used to predict the power (Table 4-3 and Figure 4-7).

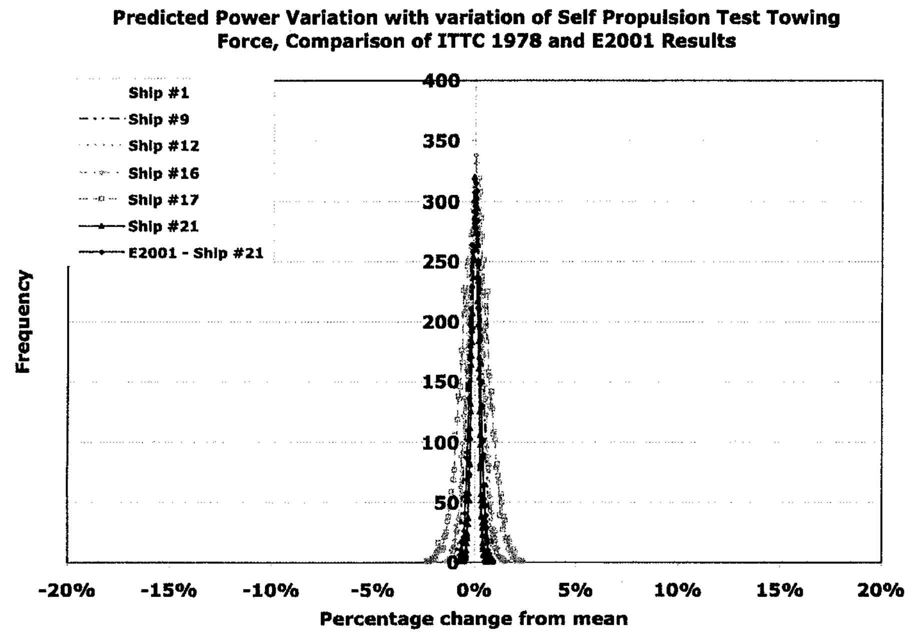

Figure 4-7 Comparison of predicted power distributions resulting when tow force was varied

4.2Variation in coefficient of friction and propulsion factors

The coefficient of friction and propulsion factors used in both the ITTC 1978 and E2001 methods were examined next. The factors were the frictional resistance coefficient, the correlation allowance, the form factor, the wake scale factor and the thrust deduction fraction. The standard deviations of the predicted results using the ITTC 1978 method detailed in Chapter 3 were compared with the standard deviations of the predicted results using the E2001 method.

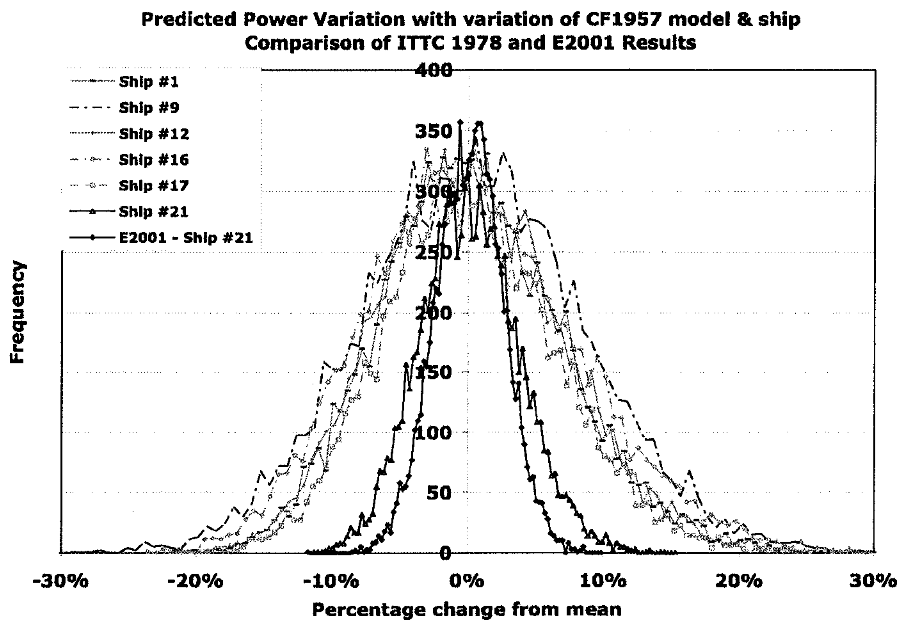

Figure 4-8 Comparison of ITTC 1978 and E2001 predicted power distributions when $C_{F\,1957}$ was varied

The frictional resistance coefficient was studied first. The standard deviation in predicted power due to a standard deviation of approximately 3% applied to the frictional resistance coefficient, $C_{F\,1957}$, was substantially higher when the ITTC 1978 method was used to extrapolate the power, 6.58%, than when the E2001 method was used, 2.51%, (Table 4-7). This is because in the E2001 method the frictional resistance coefficient is used in the determination of the tow force at the self-propulsion point only and not additionally in the interpolation of the ship propeller operating point as in the ITTC 1978 method, (see Chapter 2, Manen and Oossanen, 1988, Holtrop, 2001 and Molloy 2001).

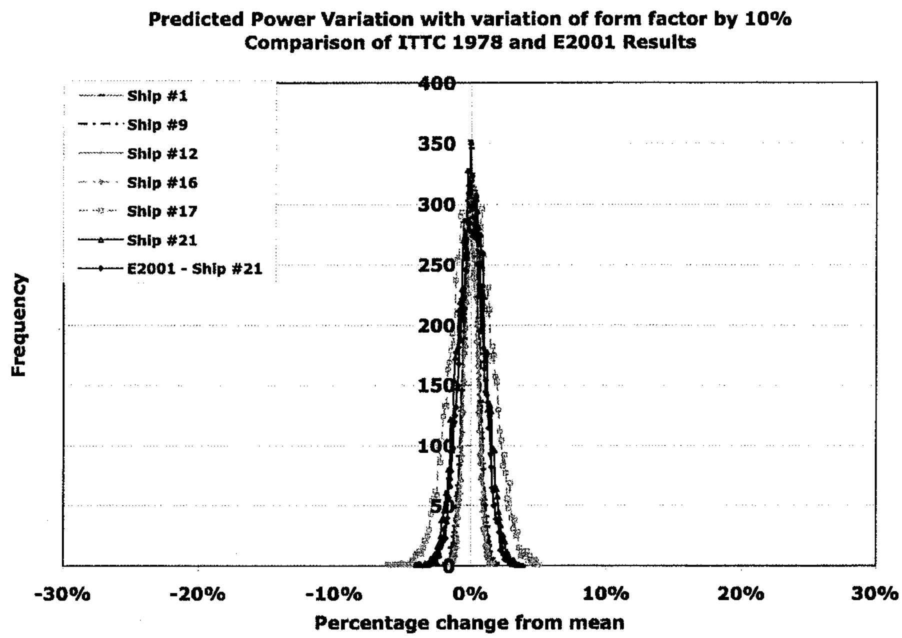

Figure 4-9 Comparison of ITTC 1978 and E2001 predicted power distributions when *k* was varied by 10%

The form factor was varied first by 10% then by 100%. Again the first percentage was chosen to represent the variation that can occur when using Prohaska's method to estimate the form factor (Manen & Oossanen, 1988). The 100% standard deviation represents the effect of choosing to use versus not use a form factor (Bose *et al.*, 2005), the nature of this variation means that in some cases a negative form factor was used in the extrapolation of power. The ships #17 and #21 had higher form factors than the remaining ships in the subset, ships #1, #9, #12 & #16 were assigned form factors of 0.1 because there were no recommended form factors in the data files and as previously discussed the Prohaska method was not automated in this program. Additionally not all the data sets in the ITTC 2005 database (Bose *et al.*, 2005) had sufficient data to calculate the form factor using Prohaska's method, as all facilities do not use the form factor and the model testing was not always presented with the required data.

Table 4-4 Comparison of predicted power when form factor was varied

	Form Factor, k, Varied 10%	**Form Factor, k, Varied 100%**
Ship #1	0.54%	5.30%
Ship #9	0.56%	5.66%
Ship #12	0.51%	5.12%
Ship #16	0.45%	4.97%
Ship #17	1.50%	14.76%
Ship #21	1.01%	9.99%
Average	***0.76%***	***7.63%***
E2001 Ship# 21	0.92%	9.25%

The standard deviation in predicted power was higher when the E2001 method was used than when the ITTC 1978 method was used when the average standard deviation of the predicted power of the subset was compared, (Table 4-4). There was a similar impact on the uncertainty of the predicted power using both the ITTC 1978 and E2001 methods. However, the average value of the subset of six ships was reduced because the form factor of four of the ships was significantly less than the form factors of ships #17 and #21 and ship #21 was used to evaluate the E2001 method.

The wake scale effect is a propulsion factor used in the E2001 method that is different to the wake fraction of the ITTC 1978 method. The wake scaling is the ratio of the ship wake to the model wake and can be based on a database of existing information; it is used to represent the scale effect on the advance velocity and is incorporated in the thrust and torque coefficients equations to obtain the representative ship curves e.g. $K_{TS} = a_1\left(w_{scale}J\right)^2 + b_1\left(w_{scale}J\right) + c_1 - \Delta K_T$ and $K_{QS} = a_1\left(w_{scale}J\right)^2 + b_1\left(w_{scale}J\right) + c_1 - \Delta K_Q$.

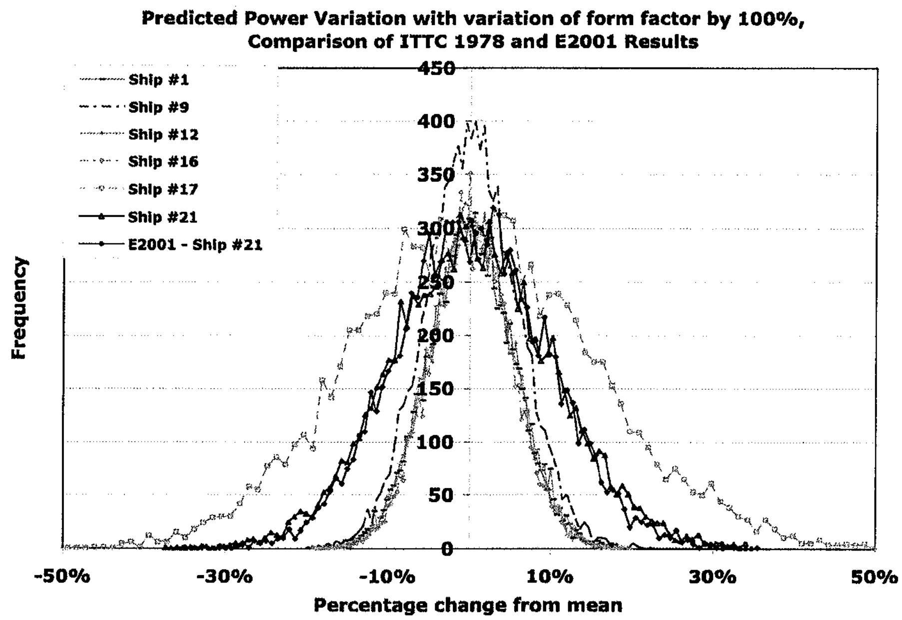

Figure 4-10 Comparison of ITTC 1978 and E2001 predicted power distributions *k* was varied by 100%

The data that are extrapolated in the E2001 method are in the behind ship condition; the self-propulsion test data, and the wake scaling is applied to correct the data to full-scale values. However, in the ITTC 1978 method the propeller open water data are used to predict the ship scale operating parameters and the data are included in an interpolation equation used to determine full-scale parameters along with the ship wake fraction (scaled using a regression equation, model wake and the thrust deduction fraction (Chapter 2, Manen and Oossanen, 1988)) and thrust deduction fraction. The correction is applied to the interpolation formula, $\dfrac{K_{TS}}{J^2} = \dfrac{S_s}{2D_S^{\,2}}\dfrac{C_{TS}}{(1-t)(1-w_{TS})^2}$ in the ITTC 1978 method rather than to the self-propulsion data curve as in the E2001 methods. The effect of the wake scaling and the wake fraction is considered to be approximately the same for both methods.

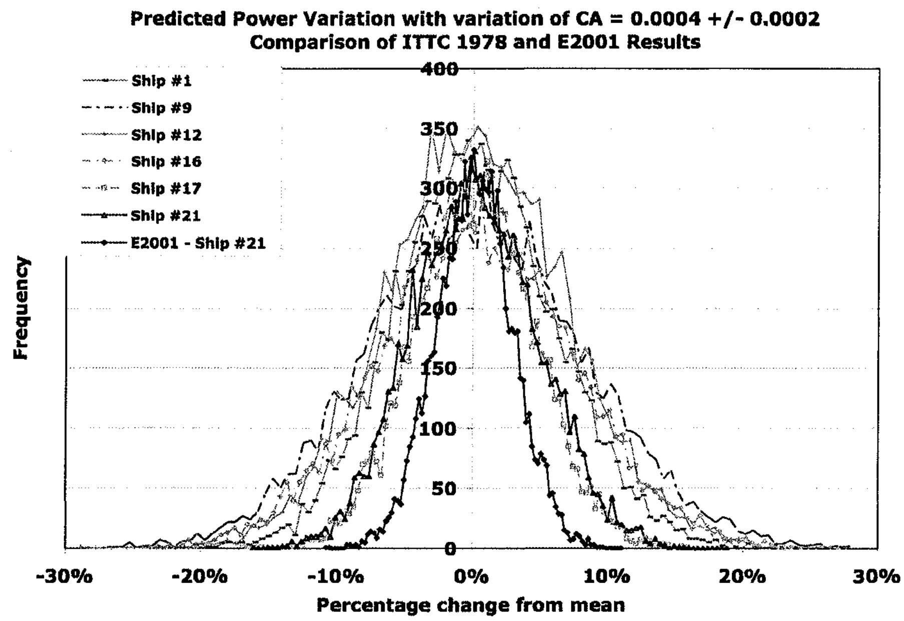

Figure 4-11 Comparison of ITTC 1978 and E2001 predicted power distributions when C_A was varied

The correlation allowance was assigned a value of 0.0004 and a standard deviation of 0.0002 for the ship data analysed using the E2001 method, the same as the values used for the data sets analysed using the ITTC 1978 method in Chapter 3. When the correlation allowance was varied alone the standard deviation of predicted power returned when using the E2001 method was less than half the average predicted power standard deviation using the ITTC 1978 method, 2.85% versus 6.14%.

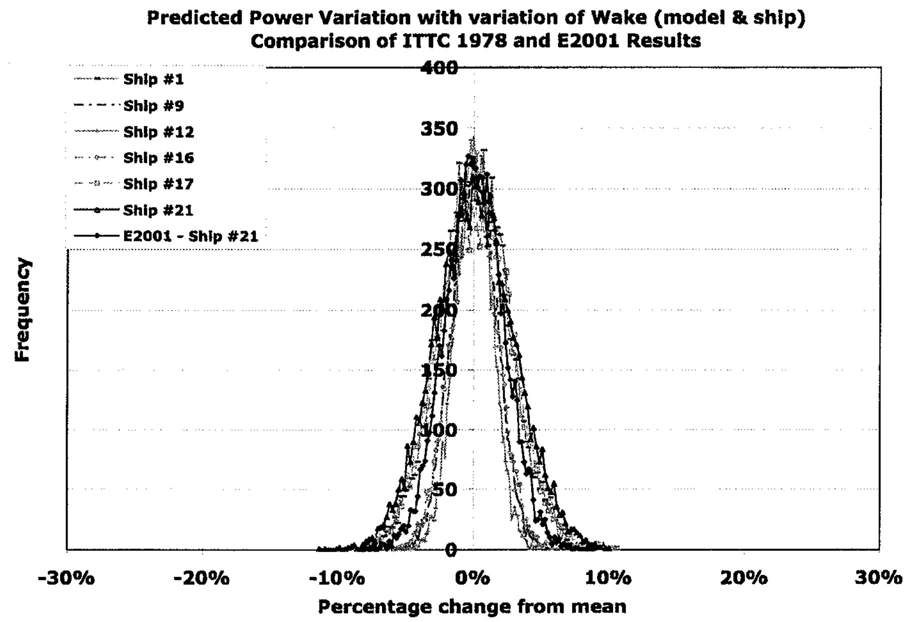

Figure 4-12 Comparison of the standard deviation in predicted power when the wake and wake scaling are varied

The wake scale effect was varied by ± 3% in the E2001 method and the standard deviation in the predicted power was compared to the standard deviation predicted using the ITTC 1978 method when the wake was varied by ~10%, Figure 4-12. The amount of ±3% standard deviation was chosen because it was the maximum value that could be used; larger values shifted the curves of the thrust and torque coefficients so far that the ship propeller operating point could not be properly estimated using interpolation.

The standard deviations of the predicted power are almost equal, a result that shows that the standard deviation in the two approaches to wake in the methods cause similar standard deviations in power.

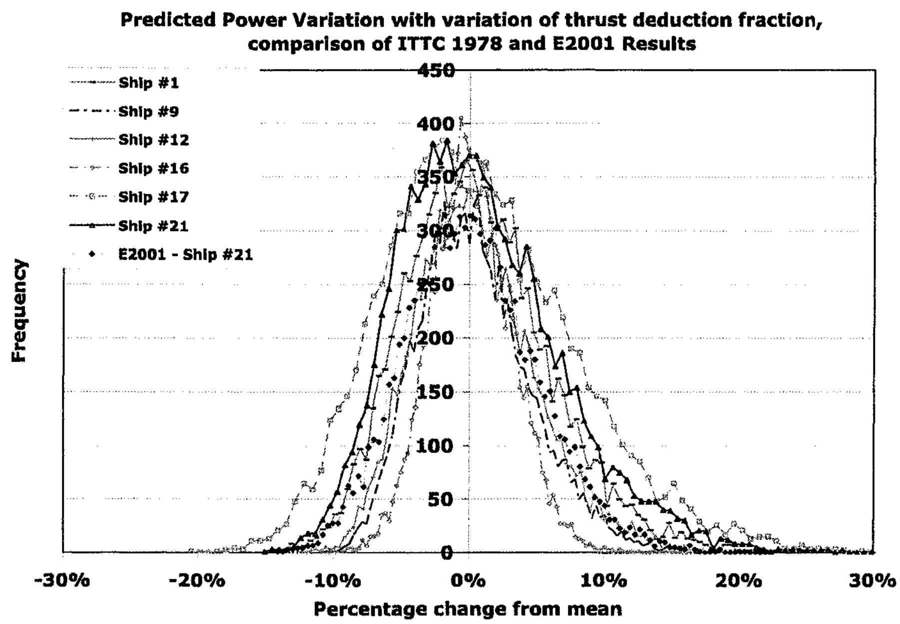

Figure 4-13 Comparison of the standard deviation in predicted power when the thrust deduction fraction was varied

Figure 4-13 shows the distributions of the predicted power when the thrust deduction fraction was varied. The thrust deduction fraction is used directly in the determination of full-scale thrust in the E2001 method, $T_S = \left\{\frac{F_{T=0} - F_D}{1-t}\right\}\lambda^3 \frac{\rho_S}{\rho_M}$ (Iannone, 1997 and Molloy, 2001) and it was expected that this propulsion factor would have a large impact on the predicted power when varied. While the thrust deduction fraction is used for the same purpose in both methods, the equations where it is incorporated differ and the impact of variation in the thrust deduction fraction results in a higher uncertainty using the E2001 method than when using the ITTC 1978 method. The standard deviation of the predicted power using the E2001 method was 4.85% when the thrust deduction fraction was varied by 10% and the average standard deviation was 2.25% using the

ITTC 1978 method. The value of 10% was chosen as representative of the potential standard deviation across a number of test speeds (section 3-3).

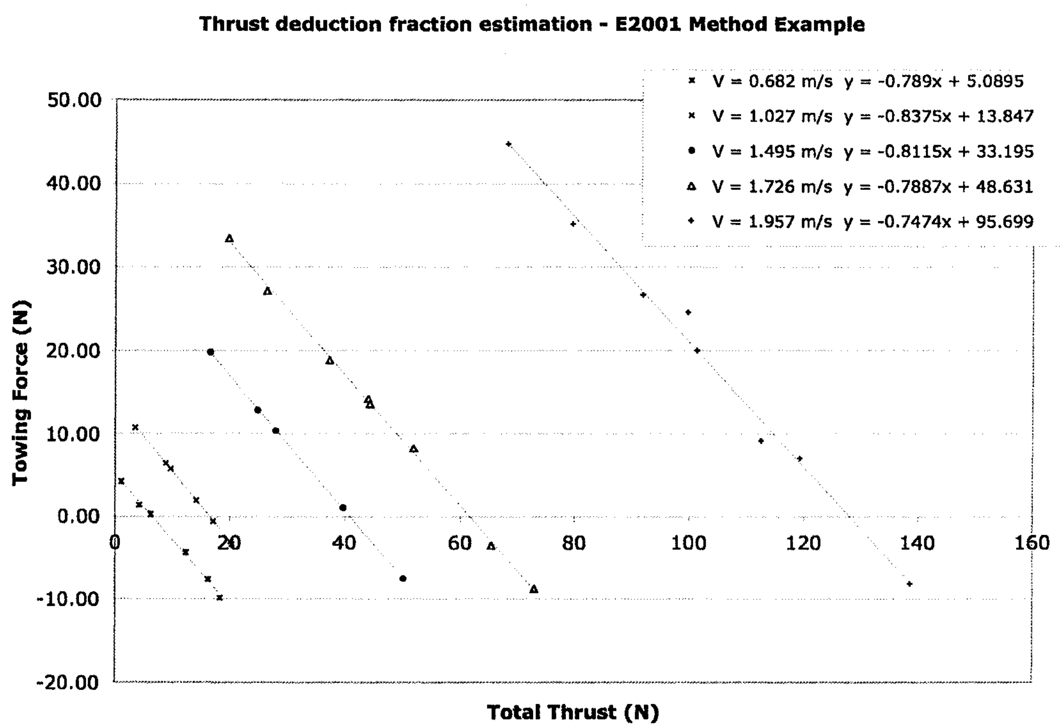

Figure 4-14 Example of thrust deduction fraction estimation, E2001 method

Using the E2001 method to obtain the thrust deduction fraction (Figure 4-14), and the equation $F_D = T_M(t-1) + F_{D@T=0}$ (see Chapter 2, Molloy, 2001 and Jessup *et al.*, 2002), ranges of standard deviation similar to those in Table 3-21 are possible, (Molloy & Bose, 2001). In fact for ship #21, the sample data used in the example in Table 4-5, the range of thrust deduction was greater than the range in Table 3-21, however this can be attributed to the fact that the range of speeds was much wider than in the data sets used in Table 3-21.

Table 4-5 Thrust deduction fraction variation with speed

Governing equation:	$F_D = T_M(t-1) + F_{D@T=0}$
V_m	Thrust deduction fraction t
[m/s]	
0.682	0.2110
1.027	0.1625
1.495	0.1885
1.726	0.2113
1.957	0.2530
Max % Diff	44.09%
Standard Deviation	0.0334

Table 4-6 Comparison of predicted power standard deviation when *t* was varied

[illegible]	[illegible]
[illegible]	[illegible]
Ship #1	2.11%
Ship #9	1.65%
Ship #12	1.76%
Ship #16	1.75%
Ship #17	2.79%
Ship #21	3.45%
Average	**2.25%**
E2001 - Ship #21	4.85%

The E2001 method resulted in a higher standard deviation than the ITTC 1978 method as expected due to the way the thrust deduction fraction is used in the prediction of full-scale power. This is an indirect comparison because the thrust deduction fraction is calculated and used in different ways in each method, however, in this analysis the comparison is valid because the overall methods are being compared and sections of the methods can be approached in different ways. It should be noted that over the subset, when power was predicted using the E2001 method, the standard deviation of ship #21 was close in value to the predicted power standard deviation for ships #17 & #21 using the ITTC 1978 method (Table 4-6).

When all the coefficient of friction and propulsion factors were varied together (*k* varied by a standard deviation of 10%) (Figure 4-16 *(a)*), the standard deviation of the predicted power using the E2001 method to extrapolate was 7.06% versus 10.84% when using the ITTC 1978 method (Table 4-7). When the measured inputs from the tests were added to the variation (Figure 4-16), the values from the self-propulsion test when extrapolating with E2001 and the values from all three tests when extrapolating with ITTC 1978, the standard deviations increased to 7.30% (E2001) and 11.12% (ITTC 1978). When the standard deviation of the form factor was 100% the predicted power standard deviation using the E2001 method was 9.80% and 13.76% using the ITTC 1978 method. When the predicted power standard deviations of ship#21 were compared directly, the ITTC 1978 method returned a predicted power standard deviation of 14.78%, almost 5% higher than the predicted power standard deviation obtained using the E2001 method for the same ship. While there was high uncertainty in the predicted power using both methods, there was almost a 50% higher uncertainty when the ITTC 1978 method was used indicating that efforts to improve the uncertainty of the E2001 method over the ITTC 1978 method would be a valid approach, in particular because the improvements to the uncertainty of E2001 method would also result in improvements to the ITTC 1978 method (see Chapter 6).

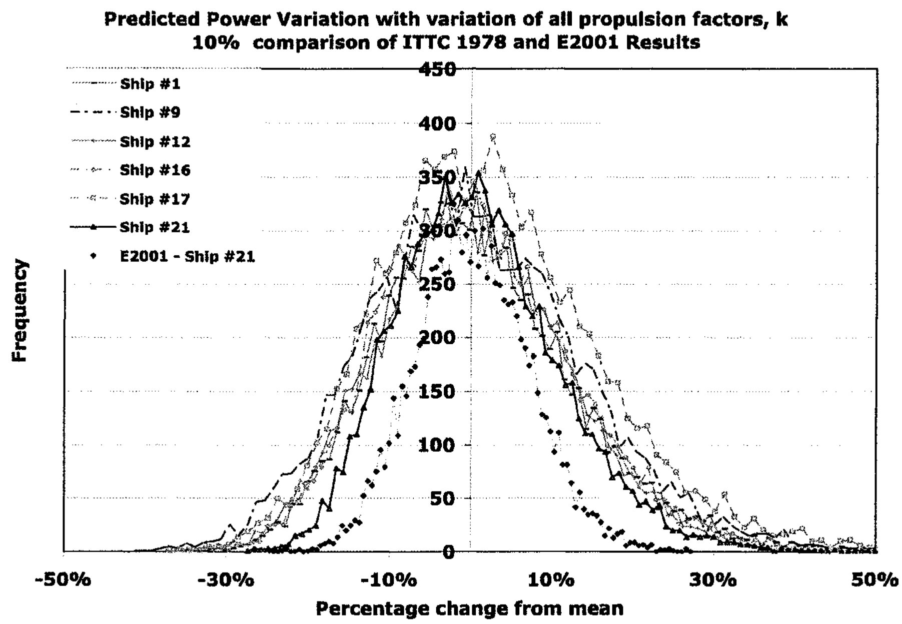

Figure 4-15 Comparison of standard deviation of predicted power when all propulsion factors and the coefficient of friction are varied

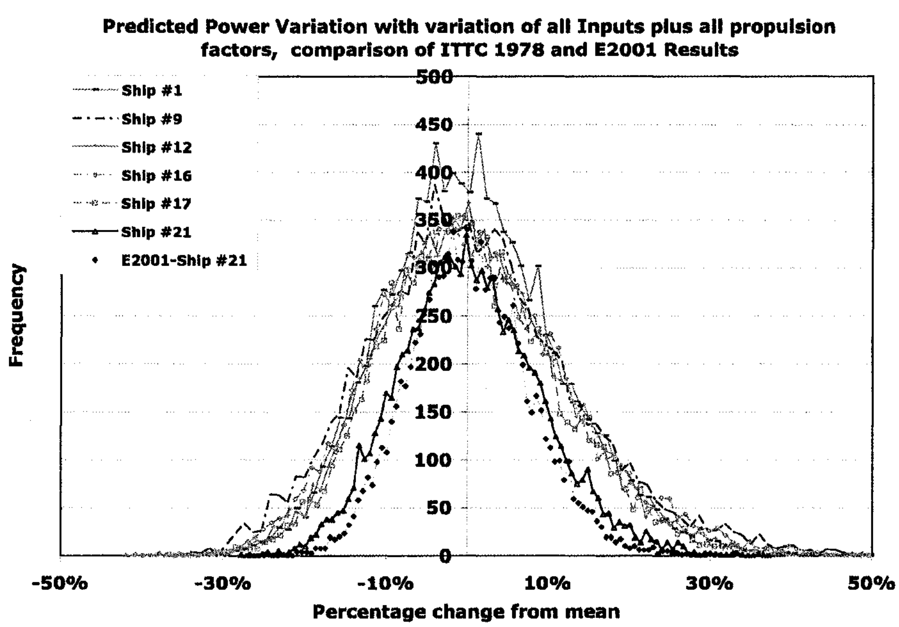

Figure 4-16 Comparison of standard deviation of predicted power when all inputs, the coefficient of friction and propulsion factors are varied together

Table 4-7 Comparison of standard deviations of predicted power when all factors and combinations are varied

	$C_{F\,1957}$ Varied 3.4% (model) and 3% (ship)	Form Factor, *k*, Varied 10%	Form Factor, *k*, Varied 100%	Correlation Allowance Varied 50%	Wake, model & ship, Varied 10%
Ship #1	6.77%	0.54%	5.30%	5.94%	2.58%
Ship #9	8.00%	0.56%	5.66%	8.00%	1.62%
Ship #12	6.81%	0.51%	5.12%	6.66%	1.38%
Ship #16	7.87%	0.45%	4.97%	7.17%	1.71%
Ship #17	6.37%	1.50%	14.76%	4.40%	2.70%
Ship #21	3.65%	1.01%	9.99%	4.65%	2.96%
Average	**6.58%**	**0.76%**	**7.63%**	**6.14%**	**2.16%**
E2001 - Ship #21	2.51%	0.92%	9.25%	2.85%	2.17%

	Thrust deduction fraction varied 10%	$C_{F\,1957}$, *k*10%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, *k*10%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, *k*100%, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied
Ship #1	2.11%	10.61%	10.85%	11.85%
Ship #9	1.65%	12.69%	13.00%	14.14%
Ship #12	1.76%	10.84%	11.23%	12.22%
Ship #16	1.75%	11.91%	12.16%	12.82%
Ship #17	2.79%	10.52%	10.79%	16.73%
Ship #21	3.45%	8.49%	8.69%	14.78%
Average	**2.25%**	**10.84%**	**11.12%**	**13.76%**
E2001 - Ship #21	4.85%	7.06%	7.30%	9.80%

The thrust deduction fraction has the most significant single factor effect on the standard deviation of the predicted power when the E2001 method was used to extrapolate the full-scale values. Figure 4-17 shows the overall standard deviation when the thrust deduction fraction was removed from the analysis; t was not varied in either the extrapolation using the E2001 method or the extrapolation using the ITTC 1978 method while the remaining parameters (including the measured test values) were varied by the previously noted amounts.

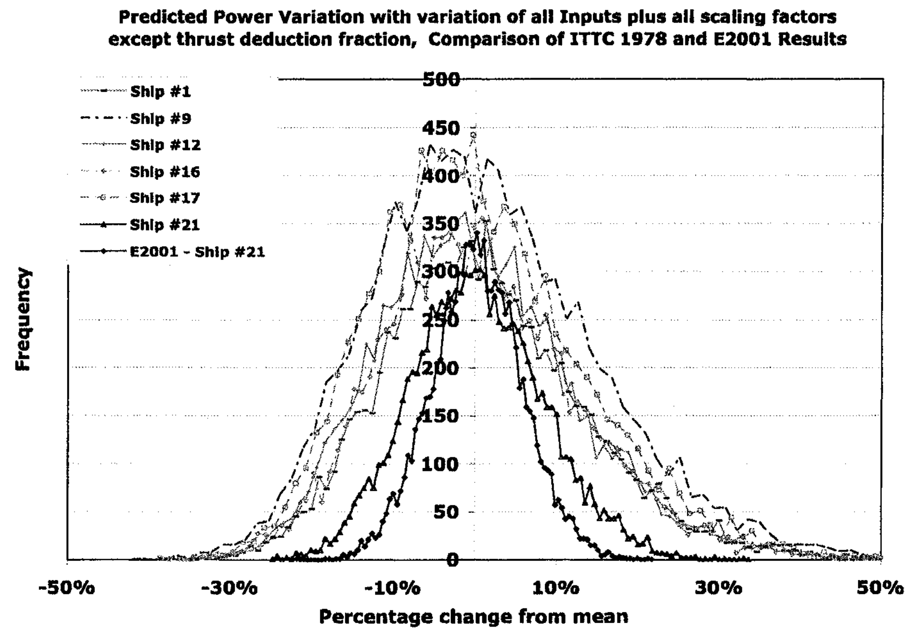

Figure 4-17 Comparison of standard deviations in predicted power when all inputs the coefficient of friction and propulsion factors are varied except the thrust deduction fraction

The average standard deviation of the subset of ships extrapolated with the ITTC 1978 method dropped by 1.34% and the standard deviation of the predicted power extrapolated using the E2001 method dropped by 4.20%. This clearly indicates that when extrapolating power using the E2001 method the predicted value was highly influenced by the thrust deduction fraction, however the result was less affected by the remaining propulsion factors than the ITTC 1978 method. The E2001 method could be improved through repeat tests or an increase of points on the tow force-thrust curve (Figure 4-14) that would decrease the uncertainty of the thrust deduction fraction and measured test values and greatly improve the stability of the method.

Table 4-8 Comparison of overall standard deviation with and without thrust deduction fraction

	All Inputs and $C_{F\,1957}$, k, Correlation Allowance, Wake (m & s), Thrust Deduction Fraction Varied	**All Inputs and $C_{F\,1957}$, k, Correlation Allowance, Wake (m & s)**
Average	***11.12%***	***11.17%***
E2001	7.30%	5.57%

4.3 Summary

The E2001 method is an alternative procedure presented for predicting ship power from model test results. When compared to the ITTC 1978 method it has been shown to predict a full-scale power that on average was less sensitive to variation in the inputs and propulsion factors with the exception of the thrust deduction fraction and the form factor (Table 4-8). The data from ship #21 was used to predict the power using both the ITTC 1978 and E2001 methods, when the standard deviations in predicted power are compared with this ship alone the E2001 predicts a smaller standard deviation in power in all the cases studied (Table 4-8). The increased amount of standard deviation in the power predicted using the E2001 method over the average power predicted over the ship range when the ITTC 1978 method was used and when a standard deviation of 10% was applied to the thrust deduction fraction, is because the thrust deduction fraction in the equation is used for the full-scale thrust estimation, $T_S = \left\{ \frac{F_{T=0} - F_D}{1-t} \right\} \lambda^3 \frac{\rho_S}{\rho_M}$ (Chapter 2).

The full-scale thrust is then incorporated in the equation $K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$, which is used to interpolate the ship power. The impact on the predicted power was also because the full-scale thrust is used directly in the calculation of the shaft speed, $n_S = \sqrt{\left[\frac{T_S}{K_{TS} D_S^4 \rho_S} \right]}$ which is then used to determine the power $P_{DS} = 2\pi \rho_S n_S^3 D_S^5 2 K_{QS}$.

The form factor is also used in the calculation of the full-scale thrust through the self-propulsion point, $F_D = \frac{1}{2} \rho_M V_M^2 S_M \left[(1+k)(C_{FM} - C_{FS}) - C_A \right]$.

If an alternative approach such as the E2001 is used to predict ship power, uncertainty in the coefficient of friction and the correlation allowance can be used in a way that has less impact on the corresponding uncertainty in power. This would allow testing facilities more flexibility in the choice of approach to obtaining the frictional coefficient (i.e. to use the ITTC 1957 approach or that proposed by Schlichting (1987) or Grigson (2001)) and in the choice of correlation allowance, of particular importance when predicting the full-scale power of newer propulsion systems because the full-scale trials that allow the validation of correlation allowances and of predicted results in general are not currently readily available, they are considered proprietary information by most ship owners.

Chapter 5

Improving the ITTC 1978 powering prediction method

The ITTC 1978 method of ship powering prediction has been shown to result in significant uncertainty in the predicted power when there is uncertainty in all the inputs and in particular, in the frictional resistance coefficient, the correlation allowance and the form factor (Table 3-27). When the frictional resistance coefficient was varied by a standard deviation of approximately 3.4% (model) and 3% (ship) the corresponding average standard deviation in predicted power is high, with a 95% confidence test, an average of ±12.89% when the coefficient is varied alone and ±21.8% (with 95% confidence) when varied with all the other factors studied. When the correlation allowance was varied alone by a standard deviation of 50% (to represent the choice between a C_A of 0.0002, 0.0004 and 0.0006) the average uncertainty in the power with 95% confidence is ±12.03%. The form factor has been shown to produce an average uncertainty of ±14.96% when the decision of whether or not to use a form factor is evaluated by applying a standard deviation of 100% to the form factor. When the form factor was varied by a standard deviation of 100% in combination with variations in the other inputs and propulsion factors studied here, the uncertainty in the predicted power with 95% confidence is ±26.97%.

Of all the inputs and propulsion factors used in the E2001 method, the variation in the thrust deduction fraction produced the largest uncertainty in predicted power, 4.85% (Table 4-7). It has been shown in section 4.3 that the effect of the thrust deduction fraction on the uncertainty in the predicted power is due to the use of the thrust deduction fraction in the estimation of the full-scale thrust, which in turn is used to predict the full-scale power. There are fewer uses of propulsion factors to be considered when predicting power using the E2001 method than when using the ITTC 1978 method, yet both methods have been shown previously to yield predicted power values close to trials values (Molloy, 2001).

One approach to improving the ITTC 1978 method is to incorporate aspects of the E2001 method into the ITTC 1978 method to reduce the potential uncertainty in the predicted power. Alternatively, the E2001 method or one similar could replace the ITTC 1978 powering prediction method entirely.

Beginning with the uncertainty in input values; the E2001 method is based on load-varying tests, which Kracht (1991) has shown improve the reliability of powering prediction. Self-propulsion load-varying tests can be used in the ITTC 1978 method without any significant changes in the prediction procedure, just the addition of a model self-propulsion point interpolation but with some increased test time and cost.

Next, the frictional resistance coefficient has been shown to be a highly significant source of uncertainty in the ITTC 1978 method (and in the E2001 method), see Table 3-27 and above. The coefficient is calculated in the ITTC 1978 method using the ITTC 1957 ship model correlation line (Manen and Oossanen, 1988 and Lindgren *et al.*, 1978). The ITTC 1957 method was intended to be an interim solution that addressed the differences in prediction when using large versus small models (Manen and Oossanen, 1988). Other friction lines have been proposed for use in powering prediction instead of the ITTC 1957 correlation line, lines such as Schlichting/Prandtl line (Schlichting, 1987), the Schoenherr or ATTC line (Manen & Oossanen, 1988), the Grigson line (1999) and the line proposed by Katsui *et al.* (2003), these lines are turbulent friction lines and may more accurately represent the frictional resistance of the vessel. The frictional resistance coefficient was calculated using three methods and the values were shown in Table 3-14. This table shows that choosing one line over another can result in a difference of over 0.0001 in the frictional resistance coefficient. The potential uncertainty in predicted power if a line represents the frictional resistance poorly is high. Without full-scale ship resistance tests or flat plate tests at full-scale Reynolds numbers, these methods of determining the frictional resistance coefficient cannot be validated and at present there are limited full-scale resistance tests available. In order to improve the uncertainty in predicted power the choice of frictional resistance coefficient should be re-evaluated.

The correlation allowance is also a significant source of error and in practice is based on a database of validated model and full-scale trials data sets. Improvement of the reliability of the correlation allowance would greatly reduce the potential uncertainty in the predicted power when using the ITTC 1978 method. The database made available by the ITTC 2005 powering prediction committee, the ITTC 2005 ship database (Bose *et al.*, 2005) is a valuable source of such data sets. One way to improve the reliability of the correlation allowance is to perform a regression analysis of the data provided that includes validation of the extrapolated model data with full-scale trials to provide a valuable, cross-facility set of correlation allowances based on ship particulars. All the ships are propeller shaft propulsion systems so ideally a future database would address the choice of correlation allowances based on both ship particulars and type of propulsion system e.g. podded propulsors or Z-drives. Holtrop and Mennen (1982) have completed a statistical analysis of resistance and propulsion data that addresses this issue.

The resistance test and the value of resistance when calculated using the ITTC 1978 method has minimal impact on the uncertainty of the predicted power (section 3.2.3) and it would not be unreasonable to maintain use of the test result within the method to estimate the resistance of the model and ship. However it is equally reasonable to suggest using an alternative method of estimating the resistance even if there is a possibility that the alternative method could have a higher uncertainty than the resistance test. If self-propulsion load-varying tests are used, low thrust tests can be added to each run so that the resistance can be represented by the tow force value at zero propeller thrust. For validation, resistance from the resistance test can be compared to the estimate from the low thrust test, usually a difference of 1-4% (Holtrop, 2001). However, in shaft propulsion systems the propeller operates in the boundary layer of the ship and the flow around the ship is influenced by the inflow to the propeller; it may in fact be more appropriate to use the low thrust estimate of resistance than the resistance obtained from tests where the appendages and propeller are removed. The resistance value is not necessary in the powering prediction methods using only load varying self-propulsion tests (Molloy, 2001, Holtrop, 2001).

The thrust deduction fraction is determined within the ITTC 1978 method using one value of resistance from the resistance test (corrected for temperature), the self-propulsion test thrust and self-propulsion test tow force, $t = \frac{T + F_D - R_C}{T}$. Using the load-varied self-propulsion test the thrust deduction fraction can be estimated from a series of test runs done at different speeds on the plot of tow force versus thrust if the relationships are linear (see Chapter 2 and section 4.2). Although the thrust deduction fraction is an important source of uncertainty in the predicted power using the E2001 method (section 4.3 and above), by using the load varying tests to calculate the thrust deduction fraction, extra speeds and repeat tests can be more affordably included to increase the reliability of the result rather than needing repeats of both self-propulsion and resistance, which would be more costly.

The frictional resistance coefficient and correlation allowance are used in both methods to determine the self-propulsion point of the ship, $F_D = \frac{1}{2}\rho_M V_M^2 S_M\left[(1+k)(C_{FM} - C_{FS}) - C_A\right]$. However, because the E2001 method does not use the frictional resistance coefficient and correlation allowance in the same way as the ITTC 1978 method in the ship propeller operating point interpolation equation, ($K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$ is used in E2001 (Iannone, 1997 and Molloy, 2001) and $\frac{K_{TS}}{J^2} = \frac{S_S C_{TS}}{2D_S^2(1-t)(1-w_{TS})^2}$ is used in the ITTC 1978 method (see Chapter 2 and Manen & Oossanen (1988)) the effect of the frictional resistance coefficient and the correlation allowance on the predicted power is much less in the E2001 method than in the ITTC 1978. The predicted power standard deviation was 2.51% versus 6.58% when the frictional resistance coefficient was varied in the previous analysis (section 4.2) and 2.85% versus 6.14% when the correlation allowance was varied. If the ITTC 1978 method ship propeller operating point interpolation equation, $\frac{K_{TS}}{J^2} = \frac{S_s}{2D_S^2} \frac{C_{TS}}{(1-t)(1-w_{TS})^2}$, is changed for the equation used in the E2001 method, $K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$, the frictional resistance coefficient, the correlation allowance and the thrust deduction fraction will all have a smaller influence on the predicted power. In order to change the ITTC 1978 method to use the interpolation equation, $K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$, the method would require that the full scale thrust be predicted using the results of a load-varied self-propulsion test and the following equation $T_S = \left\{\frac{F_{T=0} - F_D}{1-t}\right\}\lambda^3 \frac{\rho_S}{\rho_M}$ (Chapter 2, Iannone, 1997 and Molloy, 2001). The open water test has been shown to have a small impact on the uncertainty of the predicted power in section 3.2.2 and is not required in the load varying self-propulsion test only powering prediction method. However, the model torque value used to calculate full-scale torque and power could be taken from either the load-varied self-propulsion test or from the results of an open water propeller test using the thrust coefficient of the self-propulsion point of the load-varied self-propulsion test as is done in the ITTC 1978 method even though it would add steps to the process (Chapter 2 and Manen and Oossanen, 1988).

Overall, the ITTC 1978 method needs to be reviewed and updated. The method has been shown to be highly sensitive to variation in propulsion factors and the ship propeller operating point interpolation equation is a primary source of instability with in the method. Options are available and have been presented above; use a self-propulsion test only method such as the E2001 method (Molloy & Bose 2001, Holtrop 2001) or modify parts of the method through the use of alternative equations and interpolation methods that can be easily incorporated into the ITTC 1978 method.

Chapter 6

Conclusions

Extrapolation of model ship test data to full-scale values has presented many challenges since William Froude's experiments on the H.M.S. Greyhound in 1874. Geometrically similar models of full-scale designs are constructed and tested in towing tanks where the resistance of the model is measured along with the performance of the propeller. The difficulty in obtaining dynamic similarity between the model and full scale has necessitated the introduction of a frictional resistance coefficient, C_F, and a series of propulsion factors, which are based on empirical data.

Three types of tests have become standard: resistance tests, open water tests and self-propulsion tests. A resistance test measures the drag on the model through the water at a selection of velocities. An open water test measures the thrust and torque of the propeller in uniform or open flow at a selection of advance ratios. A self-propulsion test is closest to modelling the full-scale conditions, a model of the vessel is tested with a model of the propeller and the thrust, torque and shaft speed of the model are measured at a selection of velocities. When being tested, the boundary layer of the model is proportionally thicker than the boundary layer of the full-scale ship so a towing force is applied to the model in a self-propulsion test to overcome the additional resistance.

The propulsion factors (a term used here to generalize the different values used to accommodate scale effects) that are used in powering prediction include a form factor, k, a thrust deduction fraction, t, a wake fraction, w and a correlation allowance, C_A.

The International Towing Tank Conference has long been a forum where model-ship correlation has been discussed and examined. In 1978 at the 15th conference a method was presented that incorporated the commonly used techniques of the day and compared extrapolated model results to a database of ship trial data. The method that was proposed is the ITTC 1978 Performance Prediction Method for Single Screw Ships and it has been in regular use either in the original form or by way of aspects of the method incorporated into other prediction methods in many testing facilities around the world. The aspects of the method that have been incorporated at some facilities range from the types of tests used to the choice of friction line to determine the frictional resistance coefficient to the use of some or all propulsion factors.

While uncertainty calculations can be made for each of the values that are measured during testing and these uncertainties can be propagated through the powering prediction method in use, until this work, it had not been shown how sensitive the extrapolated predicted power is to uncertainty in these measured values and the various friction lines and propulsion factors used. The data reduction equations involved in the ITTC 1978 powering prediction method combined with the use of different tests made an uncertainty analysis using the propagation of uncertainty through the method highly complex. The approach used here was to treat the entire ITTC 1978 powering prediction method, in a computer program, as one large data reduction equation and analyse the overall uncertainty using the Monte Carlo simulation technique.

A Monte Carlo simulation was used to examine the effects of variation in measured test values, frictional resistance coefficient and propulsion factors on the prediction of ship scale power. By varying the different measured values from the tests together and then individually it was possible to determine which values caused the greatest and least variation in predicted power and with analysis of this information determine how these factors interact to produce this uncertainty. Using this method it was also possible to determine which of the propulsion factors most significantly impacted the predicted power and how variation in the frictional resistance coefficient affected the predicted power. By tracing how these values are propagated through the prediction method it was determined which parts of the prediction method need to be most clearly understood to determine acceptable levels of uncertainty on the full scale power. Insel (Bose *et al.* 2005) determined that the cross-correlated bias errors have a small affect on the predicted results from resistance tests in Bose *et al.* (2005). From this work it was determined that Monte Carlo methods can be used for this type of uncertainty analysis.

Two ship powering prediction methods were examined. The first was the ITTC 1978 method and the second, a method that uses only load varied self-propulsion test data in the power prediction process and is designated here as the E2001 method. It was determined where the methods differed and why the ITTC 1978 method generally resulted in greater variation in predicted power than the E2001 when measured test values and propulsion factors were varied.

For the ships considered, there was an average of 2.1% standard deviation in predicted power when a 1% standard deviation was applied to the input values obtained from the three physical tests required by the ITTC 1978 method: resistance, open water and self-propulsion (Table 3-3).

Table 6-1 Average predicted power standard deviations, test inputs

	Self Propulsion Test					Propeller open Water Test			Resistance Test	
	V	n	F_D	T	Q	J	K_T	K_Q	V_R	R_M
Average of 6 ship subset using ITTC 1978 method	**0.89%**	**0.65%**	**0.38%**	**0.49%**	**0.89%**	**0.21%**	**1.00%**	**0.66%**	**0.86%**	**0.32%**

The test results from the propeller open water test, the resistance test and the self-propulsion test were varied individually by 1% and the average standard deviations in predicted power ranged from 0.21% to 1%, (Table 6-1), showing that there is no one source of uncertainty from the set of values that are measured during the required physical tests and that the prediction method can be considered stable with respect to these parameters. However, the 1% standard deviation of K_T from the open water test resulted in a predicted power standard deviation of 1%, showing that while the thrust coefficient does not have a large affect on predicted power it has a measurable affect.

Also, this value influences the calculation of the wake fraction and the estimation of the model scale propeller characteristics (through the thrust identity); if this value were removed from the prediction method this would lower the overall uncertainty.

Table 6-2 Average predicted power standard deviations

	$C_{F\,1957}$ Varied 3.4% (model) and 3% (ship)	Form Factor, *k*, Varied 10%	Form Factor, *k*, Varied 100%	Correlation Allowance Varied 50%	Wake*, model & ship, Varied 10% **Wake scaling – E2001*
Average of 6 ship subset using ITTC 1978 method	6.58%	0.76%	7.63%	6.14%	2.16%
E2001 - Ship #21	2.51%	0.92%	9.25%	2.85%	2.17%

	Thrust deduction fraction varied 10%	$C_{F\,1957}$, k10%, Correlation Allowance, Wake* (m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, k10%, Correlation Allowance, Wake*m & s), Thrust Deduction Fraction Varied	All Inputs and $C_{F\,1957}$, k100%, Correlation Allowance, Wake* (m & s), Thrust Deduction Fraction Varied
Average of 6 ship subset using ITTC 1978 method	2.25%	10.84%	11.12%	13.76%
E2001 - Ship #21	4.85%	7.06%	7.30%	9.80%

The standard deviation in predicted power when the coefficient of friction and propulsion factors were varied by standard deviations (see section 3.3) ranged from a low of 0.76% to a high of 7.63%, (Table 6-2). These predicted power standard deviations represent the effect of the coefficient of friction and propulsion factors on the predicted power in the ITTC 1978 method, the amount by which each parameter was varied was meant to reveal the importance of the parameter to the stability of the method rather than represent true levels of uncertainty. For further study each of the magnitudes chosen can be modified and customised for a particular test facility.

When the test values were varied together with the frictional resistance coefficient and propulsion factors, the amount of uncertainty in the predicted power was 1.96 x 11.12%=±21.8% with 95% confidence (Taylor, 1997) when the standard deviation of the form factor was 10% and ±26.97% when the form factor was 100% (Table 6-2). This amount of uncertainty is unacceptable in the prediction of ship powering. The frictional coefficient, correlation allowance and form factor have been shown to contribute most to the overall predicted power standard deviation (see chapter 3). In the ITTC 1978 method the source of the high uncertainty is attributed primarily to the interpolation equation used to determine the ship propeller operating point (see chapter 6). The relative rotative efficiency was set to 1 in the analysis of the ITTC 1978 method in order to reduce the number of factors that would be varied in the uncertainty analysis and when it was included it was found that it had minimal impact on the overall uncertainty in the method.

A number of approaches to improve the stability of the ITTC 1978 powering prediction method have been presented here.

- The input data can be improved by adding data points to the test runs and by using the load varying approach in the self-propulsion test (Kracht, 1991).
- Uncertainty in the frictional resistance coefficient is a highly significant source of uncertainty in predicted power. An alternate friction line that more closely represents the flat plate friction values over a range of Reynolds numbers could be introduced. Examples of turbulent flat plate friction lines are: the Schlichting/Prandtl line

(Schlichting, 1987) the Schoenherr or ATTC line (Manen & Oossanen, 1988), the Grigson line (1999) and the line proposed by Katsui *et al.* (2003). The 1957 ITTC prediction methods committee intended for analysts to use larger correlation allowances to accommodate for the lower ship predictions that were expected from using the ITTC 1957 ship model correlation line as a temporary measure (Manen and Oossanen, 1988). It has been shown here that uncertainty in the choice of correlation allowance has a large impact on the overall uncertainty in predicted power. Using a more accurate turbulent flat plate friction line will result in the use of a smaller correlation allowance and which in turn have an additionally smaller impact on predicted power. It is not yet clear which line should be chosen, the Grigson line, the Katsui line or another. A regression analysis of the model and ship data of the ITTC 2005 ship database could be completed using each of the available lines. An uncertainty analysis of the data used to develop the friction lines would give an uncertainty range to the frictional resistance coefficient calculated and show whether 3% is a large or small uncertainty. Grigson (2000) has shown that when friction measurements of the drag on narrow pontoons were converted to drag coefficients and then compared to the Schoenherr line the average of the measured points lay approximately 3% above the line. At present, 3% uncertainty in the friction line is a valid assumption.

- Uncertainty in the correlation allowance can be addressed through the creation of a large cross-institutional database of recommended correlation allowances based on ship particulars (and possibly in the future based also on different propulsion systems such as pods) that is built through a regression analysis of correlated model data and full-scale trials. Improvement of the reliability of the correlation allowance would greatly reduce the potential uncertainty in the predicted power when using the ITTC 1978 method. The database made available by the ITTC 2005 powering prediction committee, the ITTC 2005 ship database (Bose *et al.*, 2005) is a valuable source that provides such correlated data sets. Some testing facilities have developed correlation allowances that are used with their own prediction methods. However, as reported in *Marine Engineers Review* in 1996 (Anon.), powering predictions between testing facilities and shipyards can vary 36%-40% from the lowest to the highest predicted power when the same model is tested and results are reported for the same speed. Correlation allowances that are cross-facility and would reduce the differences between test basins would be valuable to the testing community.

- A primary source of sensitivity in the ITTC 1978 powering prediction method is attributed to the interpolation curve used to determine the ship propeller operating point $\frac{K_{TS}}{J^2} = \frac{S_s}{2D_S{}^2} \frac{C_{TS}}{(1-t)(1-w_{TS})^2}$ (see Chapter 2 and Manen and Oossanen, 1988). This curve includes many terms that are subject to interpolation and interpretation by the analyst. This equation is used to interpolate the full-scale particulars and the overall uncertainty in this equation results in a large uncertainty in the predicted power. Using the uncertainty amounts presented here, the potential uncertainty in predicted power ranges from approximately ±21% to ±27% (Chapter 6 and Table 3-27). The curve is directly dependent on the measured test values from all tests, the frictional coefficient and the propulsion factors previously presented: the correlation allowance, the form factor, the wake fraction and the thrust deduction fraction. The method should be modified to improve the uncertainty in these propulsion factors or this equation should be replaced in the method with an alternate interpolation method to remove the most significant source of uncertainty in the final powering prediction.

An interpolation equation that can be used to predict the full-scale parameters with the predicted ship scale thrust ($K_{TS} = J^2 \cdot \frac{T_S}{2\rho D_S^2 V_S^2}$, using the ship scale thrust coefficient scaled from the self-propulsion test data and not the open water test data) was proposed for use in the E2001 powering prediction method (Molloy, 2001 and Iannone, 1997). In order to substitute this equation into the ITTC 1978 method the self-propulsion test must be completed as a load-varying test so that the thrust can be extrapolated to full scale using a direct method, $T_S = \left\{\frac{F_{T=0} - F_D}{1-t}\right\}\lambda^3 \frac{\rho_S}{\rho_M}$. The ship shaft speed can then be predicted from the full-scale thrust estimate, $n_S = \sqrt{\left[\frac{T_S}{K_{TS} D_S^4 \rho_S}\right]}$ and the remaining full-scale parameters, torque, $Q_S = \rho_S n_S^2 D_S^5 K_{QS}$ and delivered Power, $P_{DS} = 2\pi\rho_S n_S^3 D_S^5 2K_{QS}$, can then be predicted using the self-propulsion test torque coefficient corrected to full-scale $K_{QS} = K_{QM} - \Delta K_Q$ using the methods described in Chapter 2 and Manen and Oossanen (1988).

Both the ITTC 1978 powering prediction procedure and the method based on load varying self-propulsion tests only are sensitive to variations in the measured test input values and in the direct variations of the coefficient of friction and the propulsion factors of the methods. The parameters that have maximum impact on this sensitivity are different in the two methods but in both methods the ship propeller operating point interpolation equation of the 1978 method uses these parameters. Through comparison of the resulting variations in power, the method based on load varying self-propulsion tests only has been shown to be less sensitive overall than the ITTC 1978 method. The uncertainty in the power predicted using the method based on load varying self-propulsion tests only was ±14.3% within the 95% confidence limit (Taylor, 1997) and using the ITTC 1978 method the uncertainty was ±21.8% within the 95% confidence limit (Table 4-7).

The uncertainty in the method based on load varying self-propulsion tests only can be improved by the addition of test runs at different loadings (data points) of the self-propulsion test and by repeating test runs of the self-propulsion test. The ITTC 1978 method requires repetition of three sets of tests to gain the same improvement from using repeat runs to improve uncertainty. The uncertainty of the thrust deduction fraction can be determined from the tow-force versus propeller thrust plot when using the method based on load varying self-propulsion tests only and can be improved by adding test runs at different loadings. Both the resistance test and the self-propulsion test require additional runs to improve the uncertainty in the thrust deduction fraction when using the ITTC 1978 method. Using only the load-varied self-propulsion tests provides an opportunity to more economically use repeat tests to improve uncertainty in the prediction of full-scale power.

In future work it would be valuable to perform a comparison of the method of uncertainty analysis presented here with the methods of uncertainty analysis presented by the ITTC 23rd Specialist committee (Day *et al.*, 2002)

In summary the ITTC 1978 method has been shown to be sensitive to variation in the coefficient of friction and the propulsion factors. The ship propeller operating point interpolation equation is a source of instability within the method. In order to minimize the potential uncertainty of the power predicted using the ITTC 1978 method, the methods of obtaining the frictional resistance coefficient, the form factor, the thrust deduction fraction and the correlation allowance must be improved through new methods, additional test runs, repeat testing or new information. The method based on load varying self-propulsion tests only is most sensitive to variation in the thrust deduction fraction; the remaining propulsion factors have significantly lower effects on the predicted power when varied than when using the ITTC 1978 method. If additional testing is used to improve the ITTC 1978 method then the uncertainty in other methods that use some of the same propulsion factors and the same frictional coefficient, such as the method that uses load varying self-propulsion tests only, will also be improved. Both the ITTC 1978 method and the method based on load varying self-propulsion tests only yield similar values of predicted power. The ITTC 1978 method needs to be reviewed and updated and is under consideration by the 25th ITTC. There are a number of options to improve the reliability in power prediction using the ITTC 1978 method; alternative methods of obtaining propulsion factors can be used, alternative equations can be used to interpolate values for extrapolation, an existing database that provides a valuable source of test data that can be used to develop empirical scale effect correction factors and load varying tests can be utilised to reduce the amount and type of testing required.

These sources of uncertainty in the powering prediction method affect the choice of margins of error that must be applied to the final results in the ship design process to accommodate for example the impact of the weather, sea state, and variation in the loading on the performance of a vessel underway. The cumulative effect of this uncertainty on the predicted required power could reach unacceptable levels of uncertainty (for example: 36%-45% difference in power between proposals from facilities predicting power for the same vessel at the same operating speed, (anon., 1996)), although it is acknowledged that the analysis presented here represents the extreme values or "at worst" levels of potential uncertainty. Without reasonable levels of uncertainty in predicted power the first step in determining the power required for a vessel is highly compromised. Improvements in the methods used to predict power are necessary and feasible with existing alternative methods.

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Addendum I

Pods

The original proposal for this project included plans to investigate the development of an extrapolation method for the prediction of powering for podded propulsors. One of the primary issues to be addressed in predicting power from pod data is the measurement of pod shell resistance so a systematic geometric series was designed to determine the effect of geometry on the performance of the pod propeller and to evaluate methods of pod shell resistance estimation. The geometric series was a set of pods that had five geometric parameters/dimensions (e.g. length, diameter) that were varied in a fractional factorial design (Montgomery, 2005). The full set then consisted of 16 different pod designs and 16 different pod shells were tested. Unfortunately due to the lack of available full-scale trials data for ships fitted with podded units, and due to delays in the manufacture of testing equipment it proved impossible to complete this task in the time available. One round of testing of the systematic series was completed and there are results from the tests of the 16 pods of the systematic geometric series. These first results are inconclusive but indicate that with future testing the design of these experiments will indicate the importance of the five geometric parameters that were varied in the test series on the powering of vessels fitted with podded propulsors. Another researcher is continuing this work.

The geometric series was designed using factorial experimental design, a method of experimental design that can be used to increase the value of multi-factor experiments (experiments where more than one factor is being observed at a time) (Montgomery, 2005). The method estimates the effects of the individual factors tested on the overall result and determines which factors most influence the outcome of the experiment. This allows the experimenter to run an additional test series that studies in detail the primary factors while legitimately treating insignificant factors as negligible.

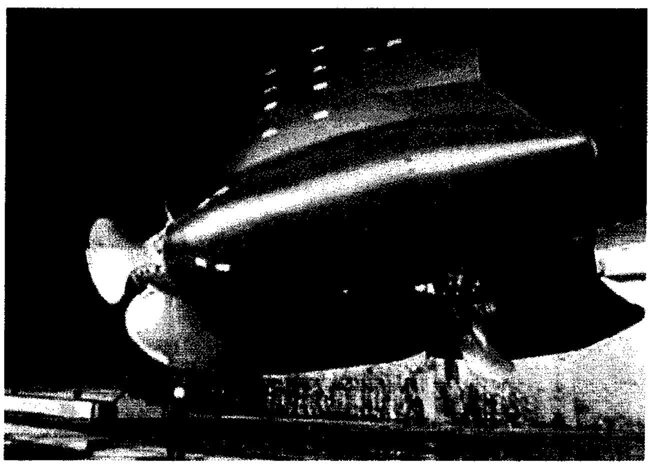

Figure I-1 Azipod from ABB, (ABB.com) (reprinted with permission)

Podded propulsors are a relatively recent addition to propulsion options for the shipping industry and are a popular alternative to traditional propulsors with ship designers. The geometry of commercial podded propulsors (Figure I-1) has been dictated by the size of the electric motors that drive the shaft.

Karafiath and Lyons (1999) of the US Navy performed resistance tests on a selection of different styles of pods, however to date there have been no published results of the effects on performance of the geometry of a pod under power. As motor design becomes more refined and flexible, the relationship of the various parameters (e.g. diameter, length, position of strut) with respect to performance becomes a more important design consideration because these factors can be optimised and it is not yet clear which geometric factors should be optimised. There are a number of geometric parameters that can be used to optimize the design of the pod and five were chosen for this test series.

The experimental investigation consisted of open water pod testingof a series of 16 pods that have geometric parameters varied using factorially designed tests. The series was limited to the analysis of 5 geometric parameters. Five parameters require 2^5 or 32 combinations to complete the test series. A fractional factorial design reduced the number of combinations by a factor of 2 by aliasing some relationships, this means that in order to reduce the number of pods required for the series some of the interactions, primarily ones with more than 2 factors, were not observable (Montgomery, 2005); 16 pods were tested in the series.

I.1 Methodology

Using commercial pods as a guide, the primary dimensions of the pod were chosen as the geometric parameters. The pod length and diameter, taper length, longitudinal position of strut, and hub angle were chosen as defining dimensions (Figure I-2) and these were varied around a mean that was determined from existing pods (Molloy, 2003).

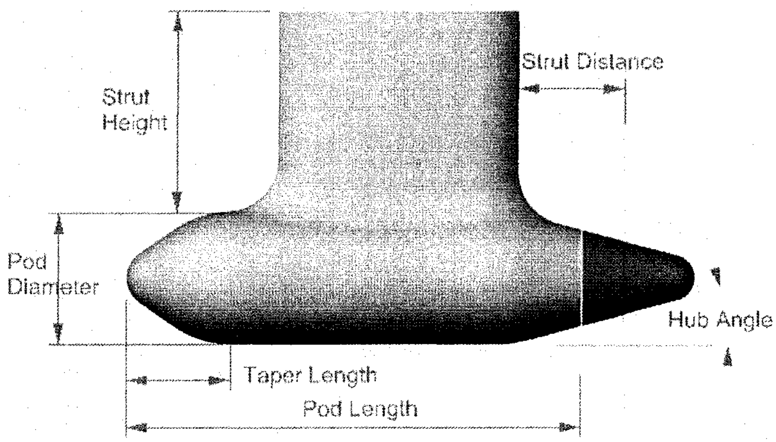

Figure I-2 Primary dimensions of pod shell

Values of the primary dimensions were chosen so that there was one set of parameters in the series that had dimensions higher than the average commercial dimensions and one set lower, Table I-1.

Table I-1 Dimensions of model pods

External Dimensions of Model Pod	Low Values	High Values
	mm	mm
Propeller Diameter	270	270
Pod Diameter	128	166
Pod Length	430	524
Strut Distance	100	133
Taper Length	69	150
Hub Angle (degrees)	15°	20°

The dimensions were then combined to produce a series of 16 pods with the combination of dimensions shown in Table I-2. The details of geometry of the propellers are given in (Islam *et al.*, 2004).

Table I-2 Combinations of dimensions for 16 pods

File/Pod Name	Factors Dprop/Dpod Diameter	Dprop/Lpod Length	Dprop/SD Strut Distance	Dprop/TL Taper Length	Hub Angle
	A	B	C	D	E
HiLo_1	lo	lo	lo	lo	lo
HiLo_2	lo	lo	hi	lo	hi
HiLo_3	lo	lo	hi	hi	lo
HiLo_4	lo	lo	lo	hi	hi
HiLo_5	lo	hi	lo	lo	hi
HiLo_6	lo	hi	hi	lo	lo
HiLo_7	lo	hi	lo	hi	lo
HiLo_8	lo	hi	hi	hi	hi
HiLo_9	hi	lo	lo	lo	lo
HiLo_10	hi	lo	hi	lo	hi
HiLo_11	hi	lo	lo	hi	hi
HiLo_12	hi	lo	hi	hi	lo
HiLo_13	hi	hi	lo	lo	hi
HiLo_14	hi	hi	hi	lo	lo
HiLo_15	hi	hi	lo	hi	lo
HiLo_16	hi	hi	hi	hi	hi

A 2 level factorial design means that in every complete set of runs of the experiment, all combinations of the high and low values of the geometric parameters in Table I-2 are studied. Using factorial design, the results of these tests indicate the relative significance of, for example, the change in pod diameter versus the change in strut distance on the performance of the pod unit. A more complex result might show that changing two geometric parameters together creates a more significant effect on the result than just changing one of the parameters individually. This is a two-factor interaction.

Fractional factorial design is a method that utilizes the experience of the researcher to reduce the number of models required, in this case from 32 to 16, by treating certain combinations as less significant and ignoring 3 and 4 factor interactions. The test series still maintains the integrity of the factorial style design. To reduce the number of combinations a relationship is set up between factors eg: E=ABCD. This relationship is called an alias and the components cannot be differentiated. Therefore a response change due to E could actually be a caused by ABCD but since ABCD is a 4-factor interaction and is being ignored, the response is considered to be that of E. All factors and combinations tested have an alias in a fractional design, however the design process ensures that the factors are not correlated (Anderson & Whitcomb 1996).

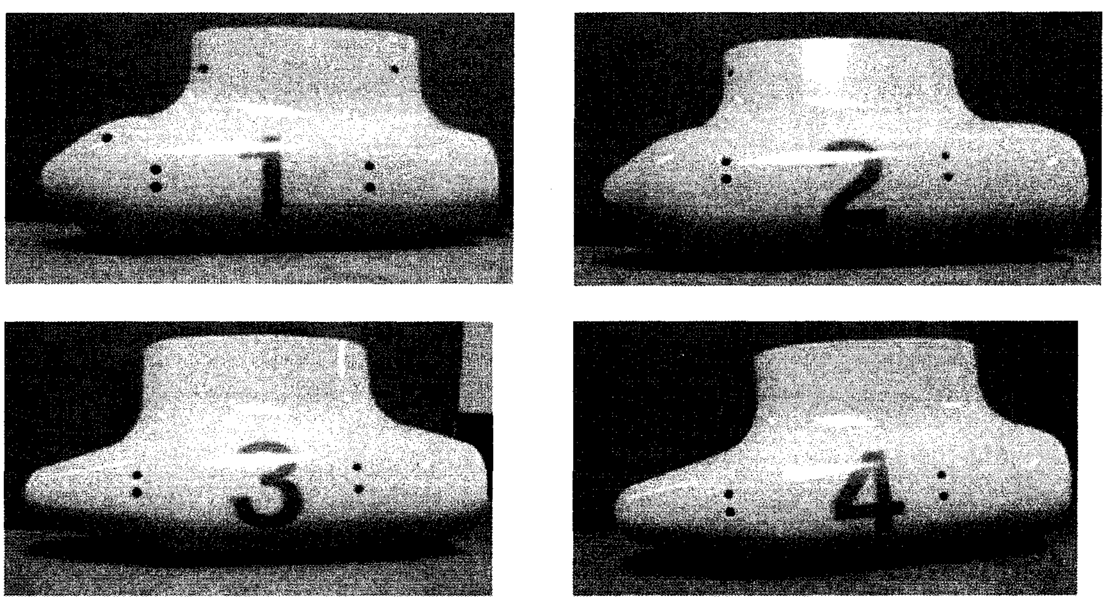

Figure I-3 Pods from the geometric series, #1 to #4

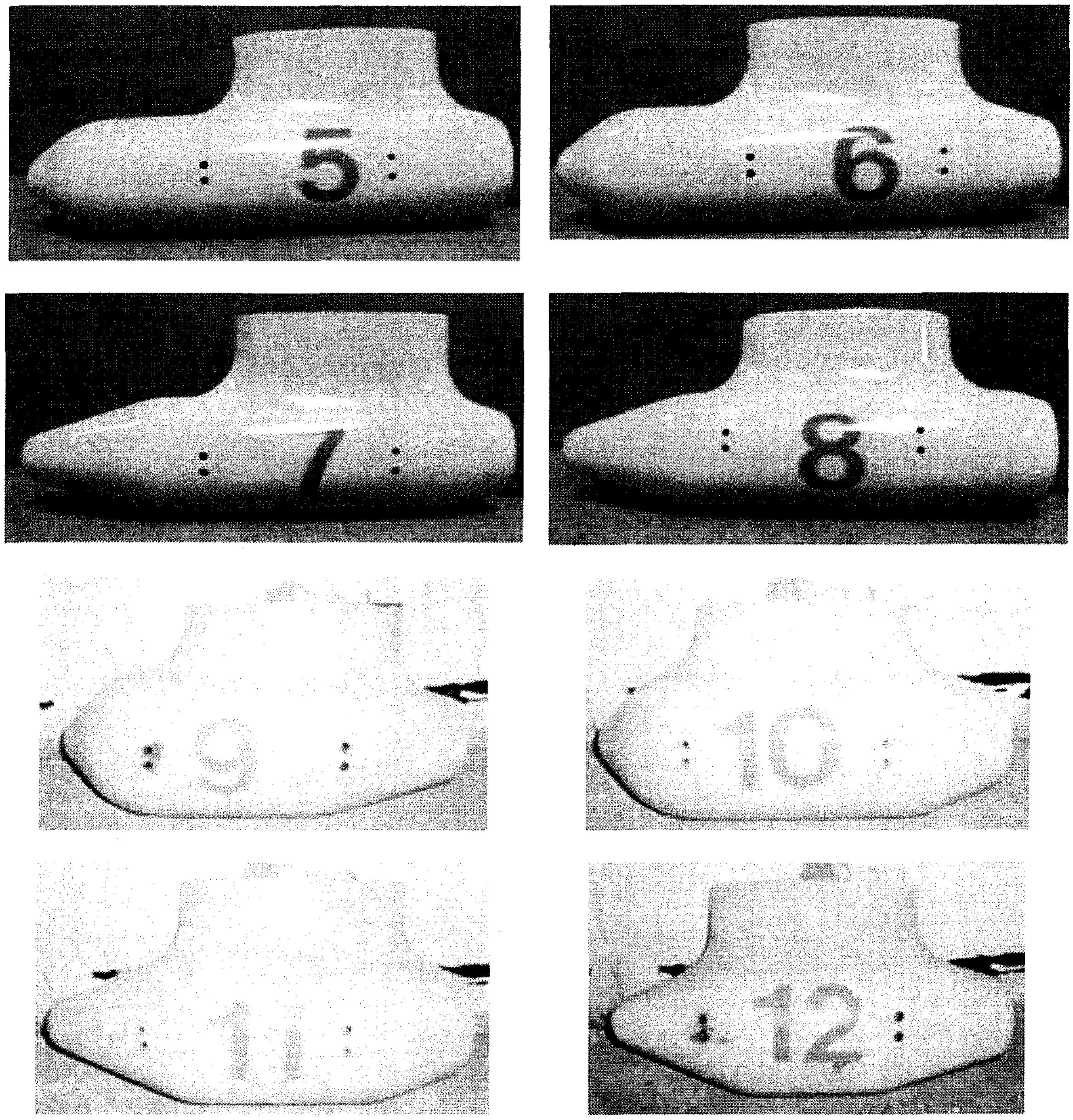

Figure I-4 Pods from the geometric series, #5 to #12

The combinations tested are listed in Table I-2 and were selected to include a combination with all dimensions low and one with all dimensions high. This decision was made to allow further testing of the largest and smallest pods directly and to allow these pods to be compared with a pod with dimensions that are an average of the dimensions of the pods in the series. Pictures of the pods are in Figure I-4, Figure I-5, and Figure I-5.

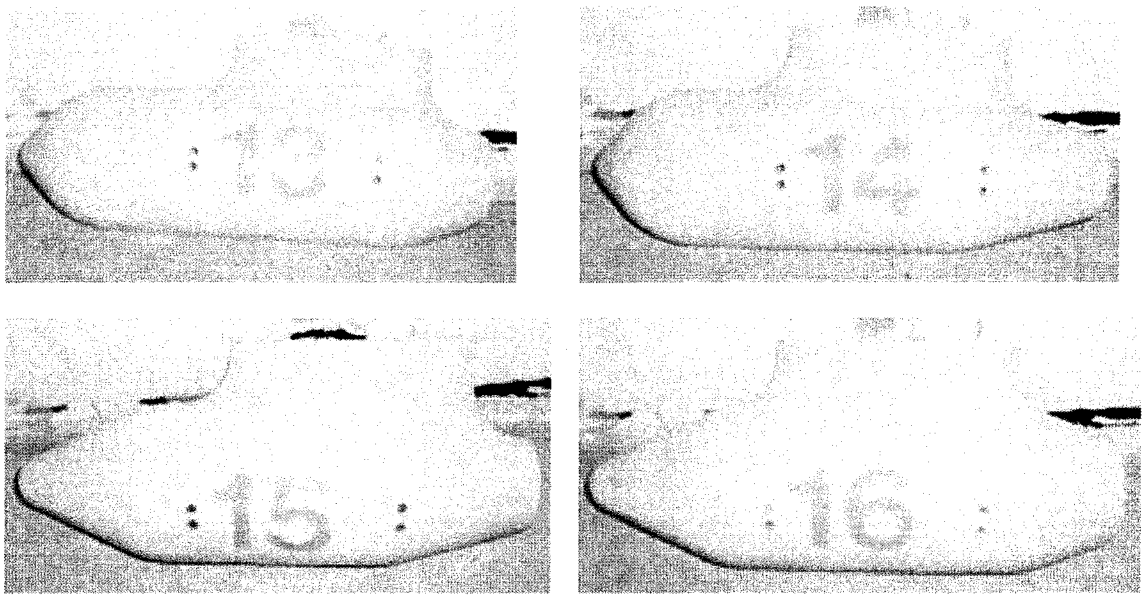

Figure I-5 Pods from the geometric series, #9 to #16

I.2 Experiments

The pods were connected to a dynamometer that was designed for this project by a co-worker (MacNeill *et al.*, 2004). Pod # 8 is shown installed in Figure I-6. The experimental setup is similar to that recommended by the ITTC 2002 Propulsion Committee (Jessup *et al.*, 2002) and by Mewis of HSVA (2001). The variables measured in each test are those required in the standard open water pod test (Jessup *et al.*, 2002): velocity of carriage, propeller rpm, propeller torque, thrust of propeller, thrust of unit.

The test set for each pod included open water pod tests at low thrust values and a number of open water pod tests at varied advance coefficients.

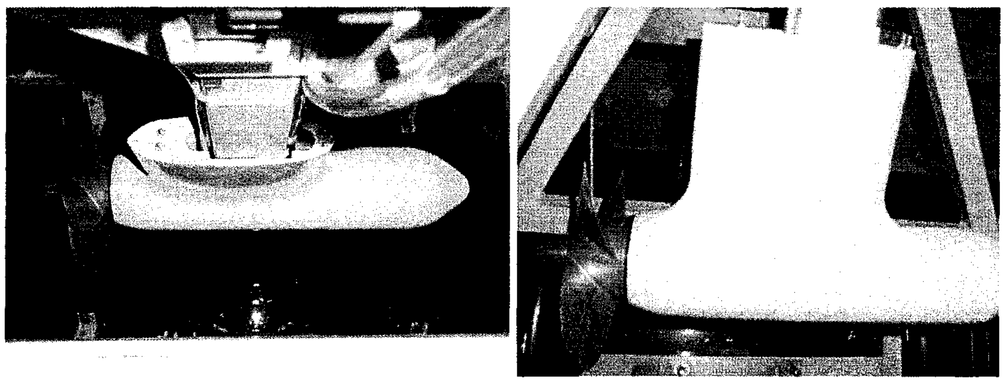

Figure I-6 Pod #8 installed on dynamometer

The pod can be run in two modes: pulling or pushing the pod unit. The tests reported here were run in pull mode, which is also referred to as tractor mode. The performance parameters that are measured by the testing dynamometer are the propeller torque measured on the shaft, the propeller thrust measured in the pod behind the shaft and the thrust of the entire unit, measured at the top of the shaft where the dynamometer connects to the towing carriage (MacNeill *et al.*, 2004).

I.3 Results

The experimental data were analyzed in terms of propeller thrust coefficient, K_T, propeller torque coefficient, $10K_Q$, and propeller advance coefficient, J (Manen & Oossanen, 1988). The powering performance results of the first set of pod experiments are presented in Figure I-7, and Figure I-8. The experiments were all conducted in the pulling mode and at 12 different advance coefficients.

Figure I-7 shows the K_T values for each pod measured from inside the pod unit from an advance coefficient of 0 to 1.1. One propeller design was used for all tests and the pitch diameter ratio of the propeller was 1.0 (Islam *et al.*, 2004). The K_T values of the different pods range from 0.41-0.51 at J = 0 and 0-0.04 at J = 1.1.

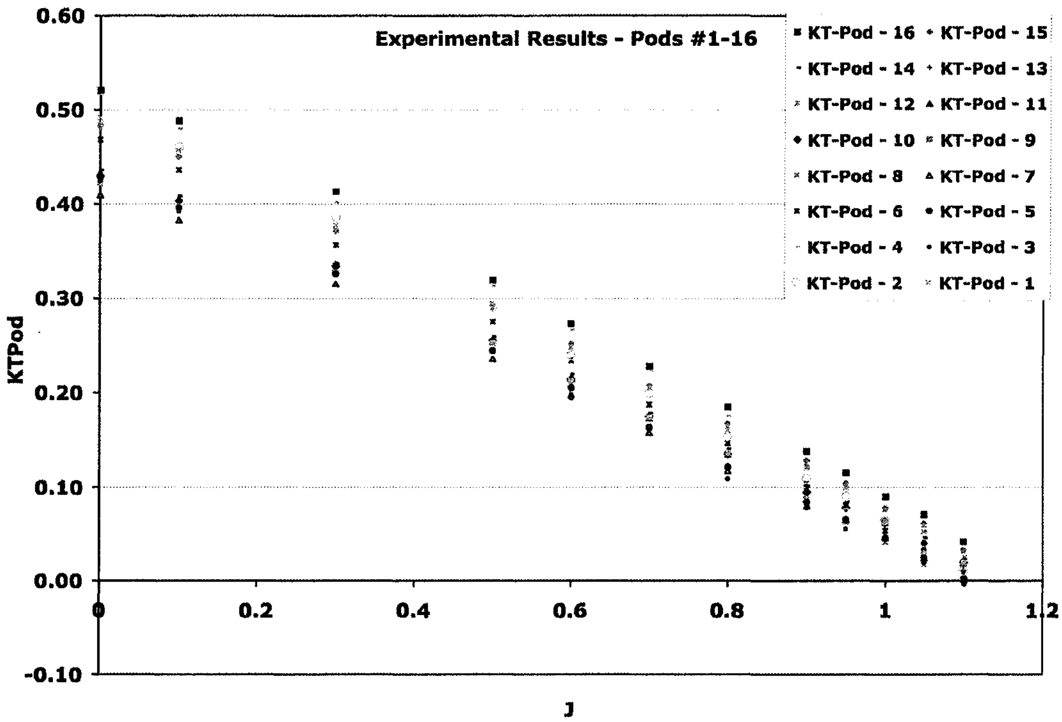

Figure I-7 Experimental results - K_{TPod} versus J for all 16 pods

Due to the factorial design, these values are not intended to be compared directly. This is because more than one geometric parameter is changed from one pod to the next so it would not be clear which factor was affecting a change if the pods were compared one-one. However, these preliminary trends show that there is some variation in thrust with the change of geometric parameters. There are three distinct groupings of pods; the highest values are for pods 4 and 16, the middle group, pods 1, 2, 6, 12 and 15 and the remaining pods in the lower group. The only common dimensions in pods 4 and 16 are the taper length and hub angle; they are both set at high values and pod 16 is the largest pod in the set. A high taper length results in a low taper angle so this means that the propeller ends of the pods were less tapered while the aft ends of the pods were more streamlined.

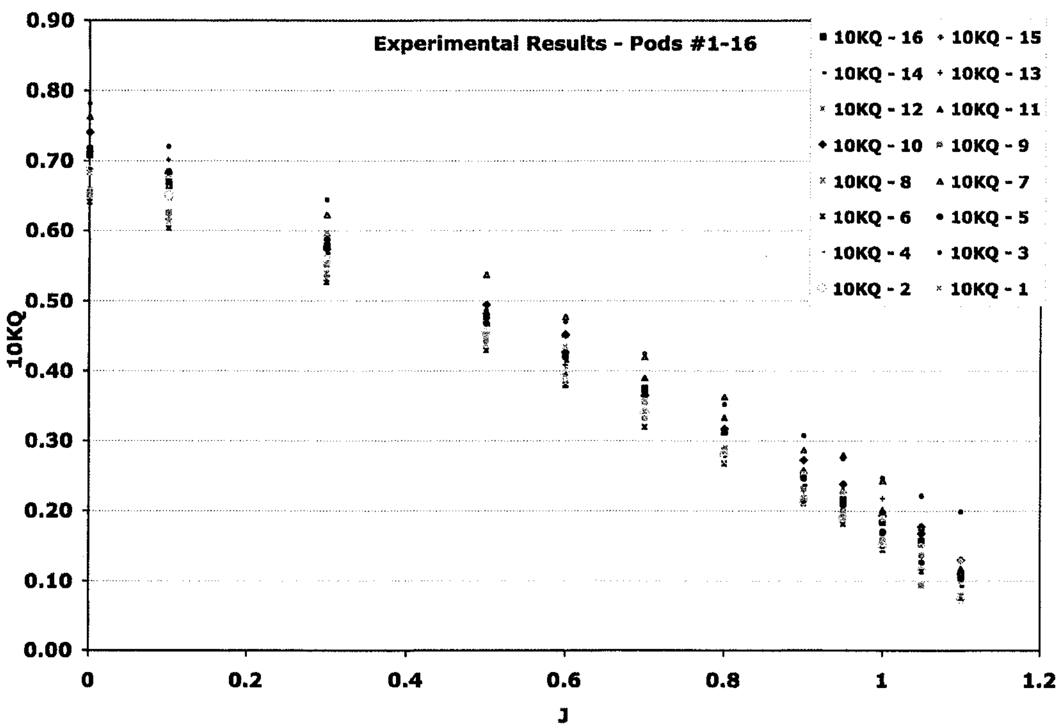

Figure I-8 Experimental results - K_Q versus J for all 16 pods

The K_Q results are shown in Figure I-8. $10K_Q$ is plotted against J and varies from 0.64 to 0.78 at J = 0 and from 0.073 to 0.19 at J = 1.1. The groupings of pods are less distinct than in the K_T plot. Pod # 3 has the highest values and pods 1, 6, 9, 12 and 15 are the lower value pods.

Figure I-9 shows the curves for the pods with all-low dimensions and all-high dimensions (pods #1 and #16 respectively). The curves indicate the magnitude of change in K_T over the range of J values for these two pods, using the same propeller.

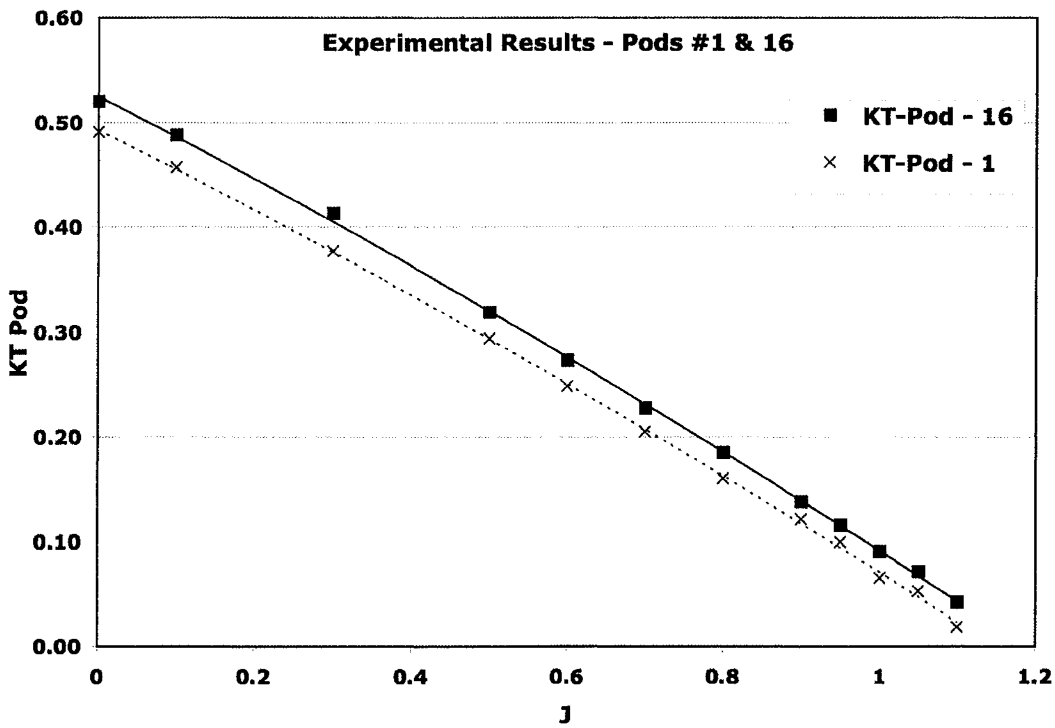

Figure I-9 K_T curves for Pods #1 & #16

Data analysis was completed using the experimental design software Design Expert®. The software allows the user to choose a factorial design that meets specific research configuration requirements; in this case the design included one pod with all-low factors and one pod with all-high factors.

The Factorial Analysis of Variance Approach (ANOVA) (Montgomery, 2005) was used to examine which geometric parameters of the series have a significant impact on the performance of the pod. The factorial ANOVA is a method of determining whether there are statistically significant main effects and statistically significant interaction effects between independent variables in a data set that have an impact on each other during the testing (e.g. the diameter and length in the pod series) (Georgetown University, http://www.georgetown.edu/departments/psychology/researchmethods/statistics/inferential/anova.htm). The significance is indicated by the F-test (Montgomery, 2005). A separate analysis was completed for each advance velocity (Table I-3).

The factors were designated as follows:

A Propeller Diameter/Pod Diameter
B Propeller Diameter/Pod Length
C Propeller Diameter/Strut Distance
D Propeller Diameter/Taper Length
E Hub Angle

For ease of explanation, in this discussion the factors are referred to without the propeller diameter, therefore A-Pod Diameter ratio, B-Pod Length ratio, C-Strut Distance ratio, D-Taper Length ratio, E-Hub Angle. The significant factors that come up repeatedly over the range of J values are Pod Diameter ratio, Pod Length ratio, Taper Length ratio, [Pod Diameter ratio interacting with Pod Length ratio], [Pod Diameter ratio interacting with Taper Length ratio] and [Pod Length ratio interacting with Taper length ratio] OR [Strut distance ratio interacting with Hub Angle]. The diameter and length ratios of the pod were expected to have a marked impact on the propeller performance, however they only appear to be significant at mid to high advance velocities and only for the torque. This result may be affected by the quality of the data from some runs as the noise error values for the low J values are quite large (>30%) and indicate that some additional testing is warranted. However, if this result proves to be reliable then at low J values the effect of the diameter and length ratios on the performance of the pod is negligible possibly because the flow rate over the pod is lower in these conditions.

Table I-3 Fractional factorial design results

Experimental Work				
J		**Significant terms**		**Noise Error**
0	K_T *Pod*		BD/CE	7.43%
	K_Q		AD, BD/CE	2.11%
0.1	K_T *Pod*	D		0.01%
	K_Q	*none*		57.54%
0.3	K_T *Pod*		BD/CE	
	K_Q			38.60%
0.5	K_T *Pod*		BD/CE	21.00%
	K_Q	*none*		25.03%
0.6	K_T *Pod*		BD/CE	3.34%
	K_Q	B	AB, AD, BD/CE	3.49%
0.7	K_T *Pod*		BD/CE	7.53%
	K_Q	*none*		36.28%
0.8	K_T *Pod*		BD/CE	2.24%
	K_Q	B		8.57%
0.9	K_T *Pod*		BD/CE	10.38%
	K_Q	A,B,	AB, BD/CE	0.30%
0.95	K_T *Pod*		BD/CE	16.54%
	K_Q	A,B	AB,AD, BD/CE	2.30%
1	K_T *Pod*	D	BD/CE	5.67%
	K_Q	A, B	BD/CE	39.20%
1.05	K_T *Pod*	D		1.66%
	K_Q	*none*		13.50%
1.1	K_T *Pod*	D		0.01%
	K_Q	*none*		57.54%

For this test series the factor combination [Pod Length ratio interacting with Taper length ratio] is aliased with the factor combination [Strut distance ratio interacting with Hub Angle] because of the choice to keep one all low pod and one all high pod in the series. This means that this highly significant factor is either the combination of the pod length ratio and taper angle ratio (BD) or the combination of the strut distance ratio and hub angle (CE). In addition, the factor taper length ratio is aliased with BCE (length ratio interacting with the strut distance ratio and the hub angle). This may not be significant as it is a 3-factor combination and will be ignored at this stage, but it may indicate that the combination of strut distance ratio and hub angle is significant. It is expected that the combination of strut distance and hub angle will significantly affect the performance of the pod unit (Islam *et al.*, 2004). It is unlikely that the taper length and pod length combination is more significant than the combination of strut distance and hub angle because the taper length was not expected to have as great an influence on the performance of the pod as the hub angle in pulling mode (Islam *et al.*, 2004).

Appendix A

Input Files Samples

Resistance Test Input File, Ship #16


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	<DATA_POINTS>
		<VDATA>
			<VR>1.95472</VR>
			<RM>86.98527000000001</RM>
		</VDATA>
		<VDATA>
			<VR>2.0576</VR>
			<RM>98.01171</RM>
		</VDATA>
		<VDATA>
			<VR>2.16048</VR>
			<RM>110.83338</RM>
		</VDATA>
		<VDATA>
			<VR>2.26336</VR>
			<RM>125.93097</RM>
		</VDATA>
		<VDATA>
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			<RM>143.20638</RM>
		</VDATA>
		<VDATA>
			<VR>2.46912</VR>
			<RM>162.85581</RM>
		</VDATA>
	</DATA_POINTS>
</RESISTANCE>
```


Open Water Input File, Ship #16


```
<?xml version="1.0" standalone="yes"?>
```

<OPENWATER>
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<KT>0.645</KT>
<KQ>0.1077</KQ>
</VDATA>
<VDATA>
<JOW>0.2</JOW>
<KT>0.591</KT>
<KQ>0.0999</KQ>
</VDATA>
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<JOW>0.3</JOW>
<KT>0.536</KT>
<KQ>0.0921</KQ>
</VDATA>
<VDATA>
<JOW>0.4</JOW>
<KT>0.479</KT>
<KQ>0.0845</KQ>
</VDATA>
<VDATA>
<JOW>0.5</JOW>
<KT>0.422</KT>
<KQ>0.0771</KQ>
</VDATA>
<VDATA>
<JOW>0.6</JOW>
<KT>0.367</KT>
<KQ>0.0696</KQ>
</VDATA>
<VDATA>
<JOW>0.7</JOW>
<KT>0.315</KT>
<KQ>0.0623</KQ>
</VDATA>
<VDATA>
<JOW>0.8</JOW>
<KT>0.265</KT>
<KQ>0.0551</KQ>
</VDATA>
<VDATA>
<JOW>0.9</JOW>
<KT>0.215</KT>
<KQ>0.0477</KQ>
</VDATA>
<VDATA>

```
            <JOW>1.0</JOW>
            <KT>0.161</KT>
            <KQ>0.0394</KQ>
        </VDATA>
        <VDATA>
            <JOW>1.1</JOW>
            <KT>0.101</KT>
            <KQ>0.0296</KQ>
        </VDATA>
        <VDATA>
            <JOW>1.2</JOW>
            <KT>0.035</KT>
            <KQ>0.0186</KQ>
        </VDATA>
        </DATA_POINTS>
</OPENWATER>
```


Self Propulsion Test Input File, Ship#16


```
<?xml version="1.0" standalone="yes"?>
<E2000INPUT>
<TSPF>2.0</TSPF>
<TSPST>14.0</TSPST>
<VISSRF>1.6704E-6</VISSRF>
<VISSPF>1.12417E-6</VISSPF>
<VISSPS>1.65988E-6</VISSPS>
<VISSPST>1.13902E-6</VISSPST>
<RHOSPF>999.9</RHOSPF>
<RHOSPST>999.0</RHOSPST>
<RHOSPS>1027.8</RHOSPS>
<G>9.807</G>
<SC>25.0</SC>
<LM>9.003999999999999</LM>
<BRDT>1.288</BRDT>
<DRGT>0.3</DRGT>
<VOL>0.954</VOL>
<DISP>2.171</DISP>
<SM>13.082</SM>
<SS>8176.25</SS>
<LBP>8.419999999999999</LBP>
<AVTM>1.2479</AVTM>
<AVTS>123.41</AVTS>
<KS>0.1</KS>
```

<KSAMP>0.00015</KSAMP>
<LS>225.1</LS>
<DM>0.232</DM>
<DS>5.8</DS>
<PD>1.293</PD>
<Z>4.0</Z>
<CM>0.06</CM>
<CS>1.2</CS>
<THM>0.005</THM>
<THS>0.1</THS>
<TPT>0.2544</TPT>
<JSPP>0.0</JSPP>
<KTSPP>0.0</KTSPP>
<KQSPPPORT>0.0</KQSPPPORT>
<KQSPPSTBD>0.0</KQSPPSTBD>
<KFDSPP>0.0</KFDSPP>
<JOMPP>0.0</JOMPP>
<KTMOPP>0.0</KTMOPP>
<KQMOPPPORT>0.0</KQMOPPPORT>
<KQMOPPSTBD>0.0</KQMOPPSTBD>
<JOSPP>0.0</JOSPP>
<KTSOPP>0.0</KTSOPP>
<KQSOPPSTBD>0.0</KQSOPPSTBD>
<KQSOPPPORT>0.0</KQSOPPPORT>
<JPT>0.0</JPT>
<KTPT>0.0</KTPT>
<KQPTSTBD>0.0</KQPTSTBD>
<KQPTPORT>0.0</KQPTPORT>
<KFDPT>0.0</KFDPT>
<NOW>11.0</NOW>
<RPT>5.0895</RPT>
<WKSC>1.0</WKSC>
<WKVAR-M>0</WKVAR-M>
<WKVAR-S>0</WKVAR-S>
<CA>0.0004</CA>
<TDVAR>0</TDVAR>
<NUMPROPS>2</NUMPROPS>
<VDATA_ROWS>
<VDATA>
    <VELOCITY>2.46912</VELOCITY>
    <REVOLUTIONS>10.2</REVOLUTIONS>
    <TOTAL_THRUST>130.473</TOTAL_THRUST>
    <TORQUE_PORT>3.3849405</TORQUE_PORT>
    <PULL>56.39769</PULL>
    <RESISTANCE>162.85581</RESISTANCE>
    <TORQUE_STBD>3.3849405</TORQUE_STBD>
    <THRUST_PORT>65.2365</THRUST_PORT>
    <THRUST_STBD>65.2365</THRUST_STBD>

```xml
</VDATA>
</VDATA_ROWS>

 <CONTROL>

<!-- provide detail about runs to perform -->

<!-- the limits of variation (spread) on either side of the corresponding vdata column value
when it is randomized -->

<VDATA_DELTA_DEFAULTS>
	<COLUMN NAME="VELOCITY" DELTA=".0246912"/>
	<COLUMN NAME="REVOLUTIONS" DELTA=".102"/>
	<COLUMN NAME="TOTAL_THRUST" DELTA="1.30473"/>
	<COLUMN NAME="TORQUE_PORT" DELTA=".033849"/>
	<COLUMN NAME="PULL" DELTA=".56397"/>
	<COLUMN NAME="TORQUE_STBD" DELTA=".033849"/>
	<COLUMN NAME="THRUST_PORT" DELTA="0.652365"/>
	<COLUMN NAME="THRUST_STBD" DELTA="0.652365"/>


	<COLUMN NAME="RM" DELTA="1.62855"/>
	<COLUMN NAME="VR" DELTA=".0246912"/>
	<COLUMN NAME="JOW" DELTA=".012"/>
	<COLUMN NAME="KT" DELTA=".00645"/>
	<COLUMN NAME="KQ" DELTA=".001077"/>


</VDATA_DELTA_DEFAULTS>



<!-- the limits of variation (spread) on either side of the corresponding constant value when
it is randomized -->

<CONST_DELTA_DEFAULTS>

	<CONSTANT NAME="WKSC" DELTA=".03"/>
	<CONSTANT NAME="KS" DELTA=".04"/>

<!-- KTSOPP=Cf Grigson model at test temperature, KQSOPPSTBD = Cf Grigson model
at standard temperature & KQSOPPPORT = CF Grigson Ship-->


	<CONSTANT NAME="KTSOPP" DELTA =".0001"/>
	<CONSTANT NAME="KQSOPPSTBD" DELTA =".0001"/>
	<CONSTANT NAME="KQSOPPPORT" DELTA =".00005"/>
```

<!—WKVAR-M - Model Wake variation – WKVAR-S - Ship Wake Variation-->

<CONSTANT NAME="WKVAR-M" DELTA="0.015"/>

<CONSTANT NAME="WKVAR-S" DELTA="0.03"/>

<!-- CA - used to vary the CA value -->

<CONSTANT NAME="CA" DELTA="0.0002"/>

<!-- TDVAR - used to vary the t value -->

<CONSTANT NAME="TDVAR" DELTA="0.05"/>

<!-- EFFRRVAR - used to vary the relative rotative efficiency value -->

<CONSTANT NAME="EFFRRVAR" DELTA="0.1"/>

</CONST_DELTA_DEFAULTS>

<RANDOMIZED_RUNS>

**<!-- one "RANDOMIZED" section for each distinct batch monte carlo run.
Each will have results stored in their own output file -->**

<!-- modifiers explained:

ITERATIONS : the number of individual runs to perform for this set

FILENAME_MOD : an identifier used for the output file. These files will share the same

name as the input XML file, replacing the .xml extension with the FILENAME_MOD value and a .txt extension.

e.g. FILENAME_MOD="norm" and original filename E-Class102SP.xml yields an output filename of E-Class102SP_norm.txt -->

<!-- this first randomization actually just outputs one result using the unmodified vdata -->

<RANDOMIZATION ITERATIONS="1" FILENAME_MOD="norm" />

```
<!-- this randomization iterates 10000 times, randomizing both VELOCITY and
REVOLUTIONS ETC. as above -->

   <RANDOMIZATION ITERATIONS="10000" FILENAME_MOD="all">

      <COLUMN NAME="TOTAL_THRUST"/>
      <COLUMN NAME="THRUST_PORT"/>
      <COLUMN NAME="THRUST_STBD"/>
      <COLUMN NAME="TORQUE_PORT"/>
      <COLUMN NAME="TORQUE_STBD"/>
      <COLUMN NAME="PULL"/>
      <COLUMN NAME="REVOLUTIONS"/>
      <COLUMN NAME="VELOCITY"/>

      <COLUMN NAME="VR"/>
      <COLUMN NAME="RM"/>
      <COLUMN NAME="JOW"/>
      <COLUMN NAME="KT"/>
      <COLUMN NAME="KQ"/>

</RANDOMIZATION>

</RANDOMIZED_RUNS>

</CONTROL>

</E2000INPUT>
```


Self-Propulsion Test Input File – Load varying data, Ship#21


```
<?xml version="1.0" standalone="yes"?>
<E2000INPUT>
<TSPF>2</TSPF>
 <TSPST>15</TSPST>
 <VISSRF>1.6704000000E-06</VISSRF>
 <VISSPF>1.1241700000E-06</VISSPF>
 <VISSPS>1.6598800000E-06</VISSPS>
```

```
<VISSPST>1.1390200000E-06</VISSPST>
<RHOSPF>999.9</RHOSPF>
<RHOSPST>999</RHOSPST>
<RHOSPS>1027.8</RHOSPS>
<G>9.807</G>
<SC>20</SC>
<LM>4.691</LM>
<BRDT>0.969</BRDT>
<DRGT>0.349</DRGT>
<VOL>0.954</VOL>
<DISP>953.7</DISP>
<SM>5.476</SM>
<SS>2084.24</SS>
<LBP>4.397</LBP>
<AVTM>0.309</AVTM>
<AVTS>123.41</AVTS>
<KS>0</KS>
<KSAMP>0.00015</KSAMP>
<LS>92.14</LS>
<DM>0.21</DM>
<DS>4.115</DS>
<PD>0.775</PD>
<Z>4</Z>
<CM>0.06</CM>
<CS>1.2</CS>
<THM>0.005</THM>
<THS>0.1</THS>
<WKVAR-M>0</WKVAR-M>
<WKVAR-S>0</WKVAR-S>
<TPT>0.2544</TPT>
<JSPP>0</JSPP>
<KTSPP>0</KTSPP>
<KQSPPPORT>0</KQSPPPORT>
<KQSPPSTBD>0</KQSPPSTBD>
<KFDSPP>0</KFDSPP>
<JOMPP>0</JOMPP>
<KTMOPP>0</KTMOPP>
<KQMOPPPORT>0</KQMOPPPORT>
<KQMOPPSTBD>0</KQMOPPSTBD>
<JOSPP>0</JOSPP>

<!-- The KTSOPP constant will be used to vary the Cf Grigson model at test temperature for the purposes of randomization & KQSOPPSTBD will be used for the Cf Grigson model at standard temperature & KQSOPPPORT will be used for the CF Grigson Ship-->

<KTSOPP>0</KTSOPP>
<KQSOPPSTBD>0</KQSOPPSTBD>
<KQSOPPPORT>0</KQSOPPPORT>
```

<JPT>0</JPT>
<KTPT>0</KTPT>

<!-- The KQPTSTBD - modifies the wake of the model & KQPTPORT modifies the wake of the ship-->

<KQPTSTBD>0</KQPTSTBD>
<KQPTPORT>0</KQPTPORT>
<KFDPT>0</KFDPT>
<NOW>11</NOW>
<RPT>5.0895</RPT>
<WKSC>1</WKSC>
<CA>0</CA>
<TDVAR>0</TDVAR>
<NUMPROPS>2</NUMPROPS>

<VDATA_ROWS>

<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>13.1</REVOLUTIONS>
<TOTAL_THRUST>68.1</TOTAL_THRUST>
<TORQUE_PORT>1.11</TORQUE_PORT>
<PULL>44.8</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.18</TORQUE_STBD>
<THRUST_PORT>34</THRUST_PORT>
<THRUST_STBD>34.1</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>13.6</REVOLUTIONS>
<TOTAL_THRUST>79.5</TOTAL_THRUST>
<TORQUE_PORT>1.26</TORQUE_PORT>
<PULL>35.2</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.34</TORQUE_STBD>
<THRUST_PORT>39.7</THRUST_PORT>
<THRUST_STBD>39.8</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>14.1</REVOLUTIONS>
<TOTAL_THRUST>91.8</TOTAL_THRUST>
<TORQUE_PORT>1.42</TORQUE_PORT>
<PULL>26.7</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.51</TORQUE_STBD>

<THRUST_PORT>45.8</THRUST_PORT>
<THRUST_STBD>46.0</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>14.5</REVOLUTIONS>
<TOTAL_THRUST>101.3</TOTAL_THRUST>
<TORQUE_PORT>1.55</TORQUE_PORT>
<PULL>20.0</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.64</TORQUE_STBD>
<THRUST_PORT>50.7</THRUST_PORT>
<THRUST_STBD>50.6</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>14.9</REVOLUTIONS>
<TOTAL_THRUST>112.5</TOTAL_THRUST>
<TORQUE_PORT>1.7</TORQUE_PORT>
<PULL>9.2</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.79</TORQUE_STBD>
<THRUST_PORT>56.3</THRUST_PORT>
<THRUST_STBD>56.2</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>15.2</REVOLUTIONS>
<TOTAL_THRUST>119.3</TOTAL_THRUST>
<TORQUE_PORT>1.79</TORQUE_PORT>
<PULL>7.1</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>1.88</TORQUE_STBD>
<THRUST_PORT>59.9</THRUST_PORT>
<THRUST_STBD>59.4</THRUST_STBD>
</VDATA>
<VDATA>
<VELOCITY>1.957</VELOCITY>
<REVOLUTIONS>15.9</REVOLUTIONS>
<TOTAL_THRUST>138.7</TOTAL_THRUST>
<TORQUE_PORT>2.04</TORQUE_PORT>
<PULL>-8.1</PULL>
<RESISTANCE>.00011</RESISTANCE>
<TORQUE_STBD>2.12</TORQUE_STBD>
<THRUST_PORT>69.9</THRUST_PORT>
<THRUST_STBD>68.8</THRUST_STBD>
</VDATA>
</VDATA_ROWS>

<CONTROL>

<!-- provide detail about runs to perform -->

<!-- the limits of variation (spread) on either side of the corresponding vdata column value when it is randomized -->

<VDATA_DELTA_DEFAULTS>
<COLUMN NAME="TOTAL_THRUST" DELTA="1.387"/>
<COLUMN NAME="THRUST_PORT" DELTA="0.6935"/>
<COLUMN NAME="THRUST_STBD" DELTA="0.6935"/>
<COLUMN NAME="TORQUE_PORT" DELTA=".0204"/>
<COLUMN NAME="TORQUE_STBD" DELTA=".0212"/>
<COLUMN NAME="PULL" DELTA=".448"/>
<COLUMN NAME="REVOLUTIONS" DELTA=".159"/>
<COLUMN NAME="VELOCITY" DELTA=".01958"/>

<COLUMN NAME="RM" DELTA=".988"/>
<COLUMN NAME="VR" DELTA=".0196"/>
<COLUMN NAME="JOW" DELTA=".0088"/>
<COLUMN NAME="KT" DELTA=".0034"/>
<COLUMN NAME="KQ" DELTA=".0004"/>

</VDATA_DELTA_DEFAULTS>

<!-- the limits of variation (spread) on either side of the corresponding constant value when it is randomized -->

<CONST_DELTA_DEFAULTS>

<CONSTANT NAME="WKSC" DELTA=".03"/>
<CONSTANT NAME="KS" DELTA=".04"/>

<!-- KTSOPP=Cf Grigson model at test temperature, KQSOPPSTBD = Cf Grigson model at standard temperature & KQSOPPPORT = CF Grigson Ship-->

<CONSTANT NAME="KTSOPP" DELTA =".0001"/>
<CONSTANT NAME="KQSOPPSTBD" DELTA =".0001"/>
<CONSTANT NAME="KQSOPPPORT" DELTA =".00005"/>

<!—WKVAR-M - Model Wake variation – WKVAR-S - Ship Wake Variation-->

<CONSTANT NAME="WKVAR-M" DELTA="0.015"/>

<CONSTANT NAME="WKVAR-S" DELTA="0.03"/>

<!-- CA - used to vary the CA value -->

<CONSTANT NAME="CA" DELTA="0.0002"/>

<!-- TDVAR - used to vary the t value -->

<CONSTANT NAME="TDVAR" DELTA="0.05"/>

<!-- EFFRRVAR - used to vary the relative rotative efficiency value -->

<CONSTANT NAME="EFFRRVAR" DELTA="0.1"/>

</CONST_DELTA_DEFAULTS>

<RANDOMIZED_RUNS>

<!-- one "RANDOMIZED" section for each distinct batch monte carlo run. Each will have results stored in their own output file -->

<!-- modifiers explained:

ITERATIONS : the number of individual runs to perform for this set

FILENAME_MOD : an identifier used for the output file. These files will share the same name as the input XML file, replacing the .xml extension with the FILENAME_MOD value and a .txt extension.

e.g. FILENAME_MOD="norm" and original filename E-Class102SP.xml yields an output filename of E-Class102SP_norm.txt -->

<!-- this first randomization actually just outputs one result using the unmodified vdata -->

<RANDOMIZATION ITERATIONS="1" FILENAME_MOD="norm" />

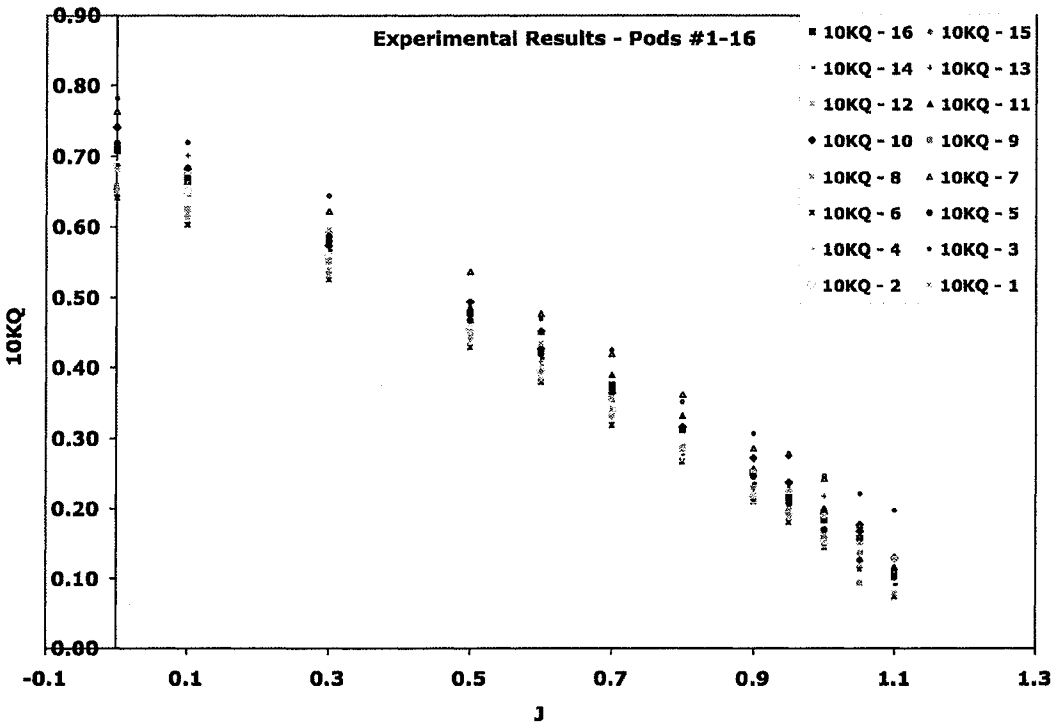
<!-- this randomization iterates 10000 times, randomizing both VELOCITY and REVOLUTIONS ETC. as above -->

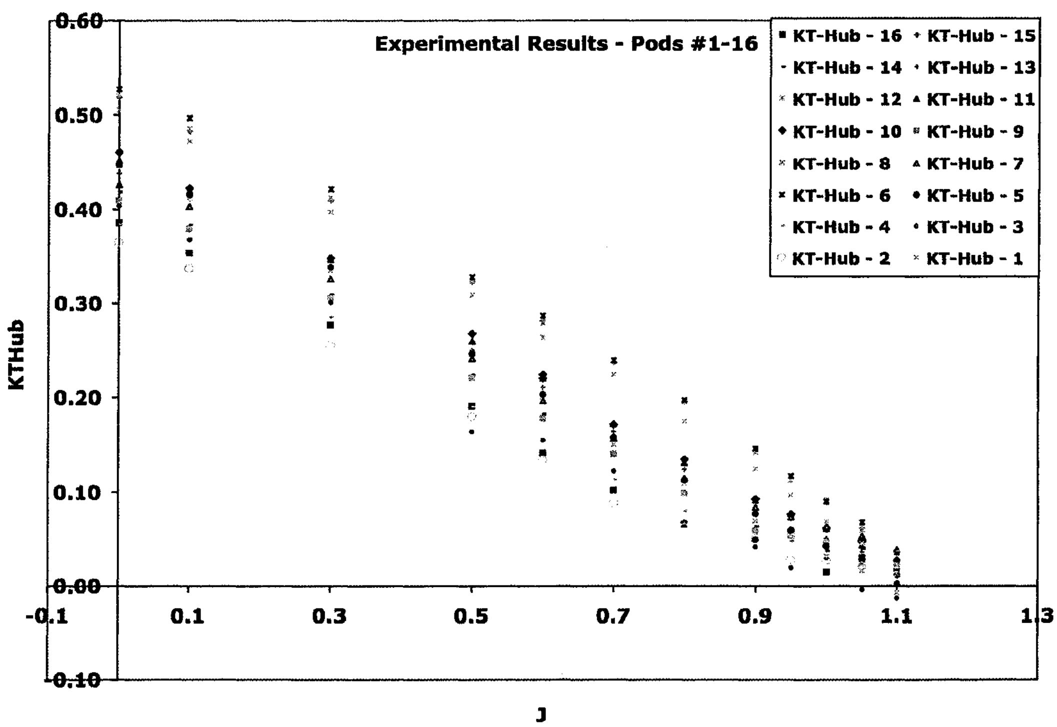
```
<RANDOMIZATION ITERATIONS="10000" FILENAME_MOD="all">

    <COLUMN NAME="TOTAL_THRUST"/>
    <COLUMN NAME="THRUST_PORT"/>
    <COLUMN NAME="THRUST_STBD"/>
    <COLUMN NAME="TORQUE_PORT"/>
    <COLUMN NAME="TORQUE_STBD"/>
    <COLUMN NAME="PULL"/>
    <COLUMN NAME="REVOLUTIONS"/>
    <COLUMN NAME="VELOCITY"/>

    <COLUMN NAME="VR"/>
    <COLUMN NAME="RM"/>
    <COLUMN NAME="JOW"/>
    <COLUMN NAME="KT"/>
    <COLUMN NAME="KQ"/>

</RANDOMIZATION>

</RANDOMIZED_RUNS>

</CONTROL>

</E2000INPUT>
```

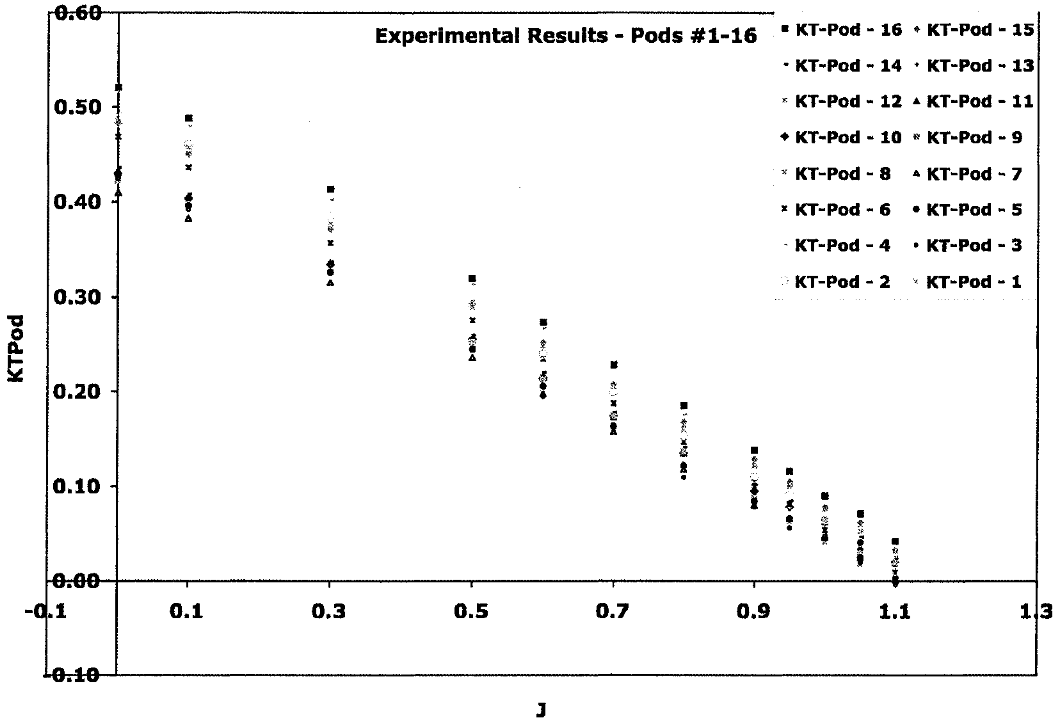
Appendix B

Pod Test Results

Standard Order	Factors					
	Dprop/Dpod Diameter	Dprop/Lpod Length	Dprop/SD Strut Distance	Dprop/TL Taper Length	Hub Angle	FileName
1	lo	lo	lo	lo	lo	HiLo_1
2	hi	lo	lo	lo	lo	HiLo_9
3	lo	hi	lo	lo	hi	HiLo_5
4	hi	hi	lo	lo	hi	HiLo_13
5	lo	lo	hi	lo	hi	HiLo_2
6	hi	lo	hi	lo	hi	HiLo_10
7	lo	hi	hi	lo	lo	HiLo_6
8	hi	hi	hi	lo	lo	HiLo_14
9	lo	lo	lo	hi	hi	HiLo_4
10	hi	lo	lo	hi	hi	HiLo_11
11	lo	hi	lo	hi	lo	HiLo_7
12	hi	hi	lo	hi	lo	HiLo_15
13	lo	lo	hi	hi	lo	HiLo_3
14	hi	lo	hi	hi	lo	HiLo_12
15	lo	hi	hi	hi	hi	HiLo_8
16	hi	hi	hi	hi	hi	HiLo_16


Experimental Results - Pods #1-16
10KQ
J
10KQ - 16
10KQ - 15
10KQ - 14
10KQ - 13
10KQ - 12
10KQ - 11
10KQ - 10
10KQ - 9
10KQ - 8
10KQ - 7
10KQ - 6
10KQ - 5
10KQ - 4
10KQ - 3
10KQ - 2
10KQ - 1
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3


Experimental Results - Pods #1-16
KTHub
J
KT-Hub - 16
KT-Hub - 15
KT-Hub - 14
KT-Hub - 13
KT-Hub - 12
KT-Hub - 11
KT-Hub - 10
KT-Hub - 9
KT-Hub - 8
KT-Hub - 7
KT-Hub - 6
KT-Hub - 5
KT-Hub - 4
KT-Hub - 3
KT-Hub - 2
KT-Hub - 1
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3


Experimental Results - Pods #1-16
KT-Pod - 16
KT-Pod - 15
KT-Pod - 14
KT-Pod - 13
KT-Pod - 12
KT-Pod - 11
KT-Pod - 10
KT-Pod - 9
KT-Pod - 8
KT-Pod - 7
KT-Pod - 6
KT-Pod - 5
KT-Pod - 4
KT-Pod - 3
KT-Pod - 2
KT-Pod - 1
KTPod
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
J